TECHNICAL BULLETIN No. 205 OCTOBER, 1930

GLUING WOOD IN AIRCRAFT MANUFACTURE

BY

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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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INTRODUCTION

The modern airplane requires from about 250 to 2,000 board feet or more of lumber and considerable quantities of veneer and plywood in its construction. It is estimated that 8,000 to 10,000 airplanes, chiefly of commercial type, were built in 1929, of which approximately 90 per cent had wing structures of wood. Even in the fast

[1] Acknowledgment is made to various members of the Forest Products Laboratory and of the War and Navy Departments for assistance in the preparation of the manuscript and to several aircraft manufacturers for contributed photographs and information.

[2] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

combat type of military plane wooden wing structures are used. In some planes the entire wing framework and covering is of glued-wood construction. (Pls. 1 and 2.) In propellers, control surfaces, fuselages, and the pontoons and hulls of seaplanes and flying boats wood is also used (*12*, *28*).[3] (Pls. 2 and 3.) A partial list of more detail parts, made wholly or partly of wood, includes: Wing beams (solid and box types), ribs, leading and trailing edges, bow ends, braces, reinforcing or shear blocks, and light compartments; aileron ribs, braces, and covering; rudder, stabilizer, and elevator parts; tank compartments; propellers; center covers, step boards and walkways; turtle decks; engine bearers; bulkheads; instrument boards; floors; seats; cabin sides; fairings; doors; strut streamlining; and keels, ribs, partitions, braces, and covering of pontoons and hulls. (Pls. 4, 5, 6, and 7.)

Glue is used not only in laminating and building up large and irregular wooden parts and in the making of plywood but it also affords the principal means of fastening the various wooden parts together into the finished structure. Joints, together with fastenings, are, however, generally regarded as the weakest part of the built-up construction. Consequently they control the design in very large part, despite the fact that it is known that the technic of gluing as practiced in aircraft is capable of considerable improvement (*22*, *23*).

Since nearly every article of glued-wood construction represents an economy in the use of timber resources the Forest Products Laboratory has conducted studies upon glues and gluing,[4] a large part of which has pertained to the use of glue in aircraft.[5] The purpose of the present bulletin is to give specific information about the gluing of wood that is directly applicable to aircraft.

GLUES FOR AIRCRAFT

Most uses of glues in aircraft require adhesives that retain a large proportion of their strength under moist conditions, even to the extent of remaining safe in service after exposure to free water. Of the various adhesives commonly used in woodworking, blood-albumin and casein glues most nearly meet these requirements.[6] This principle excludes at once the vegetable glues made from starch, as well as fish glues and untreated animal glues, which, although admirably suited for interior use, lose their strength rapidly and almost completely when exposed for even short periods to a moisture-saturated atmosphere or to free water. Only where the glued members are thoroughly protected against moisture changes by suitable coatings are any of the less moisture-resistant glues useful in aircraft. In wooden propellers, high-grade animal glue has been used successfully. Any increase in moisture content large enough

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[3] Italic numbers in parentheses refer to Literature Cited, p. 56.

[4] A general discussion of the use of glue in woodworking industries is given in The Gluing of Wood (*24*).

[5] Research conducted in cooperation with the War and Navy Departments and the National Advisory Committee for Aeronautics.

[6] This bulletin is confined to a discussion of glues that set and make strong joints in wood. Marine glues, which are used in aircraft to make constructions water-tight, are not included among the so-called woodworking glues since they do not set.

to weaken the glue seriously makes the propellers unserviceable on account of changes in shape; hence highly moisture-resistant coatings are used that protect the whole construction.

PROPERTIES OF AIRCRAFT GLUES

The principal adhesives of proved value for making wood joints in aircraft are casein glues, blood-albumin glues, and animal glues when properly protected against large moisture changes. In Table 1 the general properties and characteristics of casein, blood-albumin, and animal glues used in aircraft are listed. On most of the points of comparison there is a lack of definite and specific knowledge, and as a result only general terminology can be used in describing them. Furthermore, there is a wide variation among the glues of the three classes. Only the strongest and most durable glues of each class are described.

TABLE 1.—*Properties and characteristics of different classes of woodworking glues used in aircraft* [1]

Property or characteristic	Casein glue	Blood-albumin glue	Animal glue (untreated)
Strength (dry) [2]	Very high to medium	Medium to low	Very high.
Strength (wet after soaking in water 48 hours).	About 25 to 50 per cent of dry strength; varies with glue.	About 50 to nearly 100 per cent of dry strength.	Very low.
Durability in 100 per cent relative humidity or prolonged soaking in water.	Deteriorates eventually; rate varies with glue.	Deteriorates slowly but usually completely in time.	Deteriorates quickly.
Rate of setting	Rapid	Very rapid with heat	Rapid.
Working life	Few to several hours [3]	Several hours to a few days.	Few hours to several days.[3]
Consistency	Medium to thick	Variable, thin to thick, depending on formula.	Variable from thin to very thick with temperature changes.
Temperature requirements.	Used at ordinary room temperatures.	Heat required to set glues; cold-press formula an exception.	Control important for glue, wood, and room.
Mixing and application	Mixed with cold water; applied cold by hand or mechanical spreaders.	Mixed with cold water; applied cold by hand or mechanical spreaders.	Soaked in water and melted; applied warm by hand or mechanical spreaders.
Tendency to foam	Slight to medium	Slight to pronounced	Usually slight.
Tendency to stain wood	Marked with some woods.	None, except that dark glue may show through thin veneer.	None to very slight.
Dulling effect on tools [4]	Moderate to pronounced	Slight	Moderate.
Spreading capacity: [5]			
Extremes reported [4]	30 to 80	30 to 100	20 to 55.
Common range [4]	35 to 55		25 to 35.

[1] Grades and quality only of glues that pass U. S. Government aircraft specifications.
[2] Based chiefly on joint strength tests.
[3] Casein and animal glues are likely to deteriorate seriously if kept liquid more than 1 day.
[4] Based on reports from commercial operators.
[5] Expressed in square feet of single glue line per pound of dry glue for veneer work.

Apart from joint tests there is comparatively little specific information on the mechanical and physical properties of glues as materials of construction. Some data, however, are available on the tensile strength of animal glues (*2*, *9*, *10*, *15*, *17*) and on the relation between moisture content and relative humidity for animal and casein glues. In Figure 1 is shown the tensile strength—moisture-content relation for an animal glue that meets the specifications for aircraft work. Small specimens of the glue at different moisture content were tested in tension. The decrease in strength with increase in moisture is striking. Curves shown in Figure 2 indicate the relation of relative humidity to moisture content of the same animal glue and of one type of a water-resistant casein glue. The casein glue absorbed an even larger percentage of moisture than the animal glue, but from other tests was found to retain a greater proportion of its dry strength.

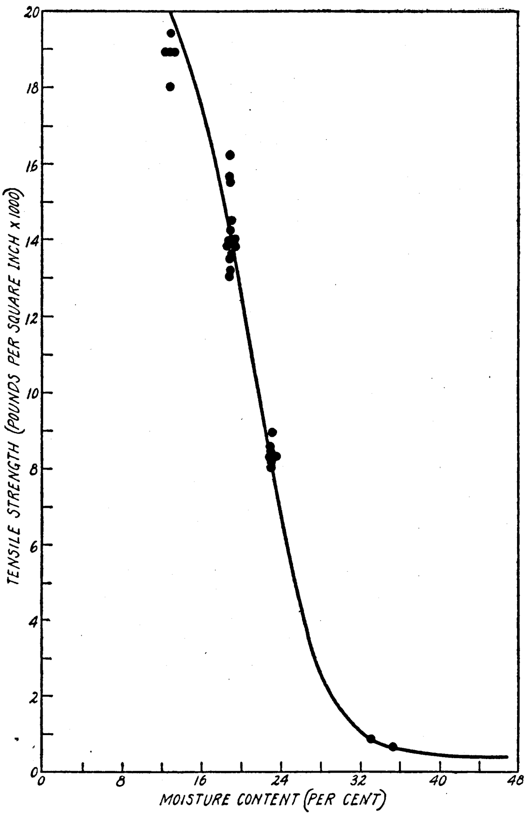

FIGURE 1.—The effect of moisture content on the tensile strength of an animal glue that meets aircraft specifications

Water-resistant glues, particularly casein and blood albumin, set on wood at almost any moisture content, but animal glue will not set on wood of high moisture content, 15 per cent being about the maximum for satisfactory results.

Animal glue treated with formaldehyde-yielding materials gives joints of about the same initial resistance in cold water as the water-resistant casein glues. However, tests indicate that it is less durable under prolonged exposure. Blood-albumin glues are less affected by soaking in water than other water-resistant glues.

Formulas for the preparation of water-resistant casein, blood-albumin, and animal glues, which rate well in water resistance among the glues of their classes and which are suitable for use in aircraft, are given on p. 52.

OTHER MOISTURE-RESISTANT ADHESIVES

Besides the glues that have been discussed there are other adhesives that compare favorably in many respects with those now in use. An improvement in one or more respects may make their use in aircraft desirable. Some of these adhesives are discussed in the next three paragraphs.

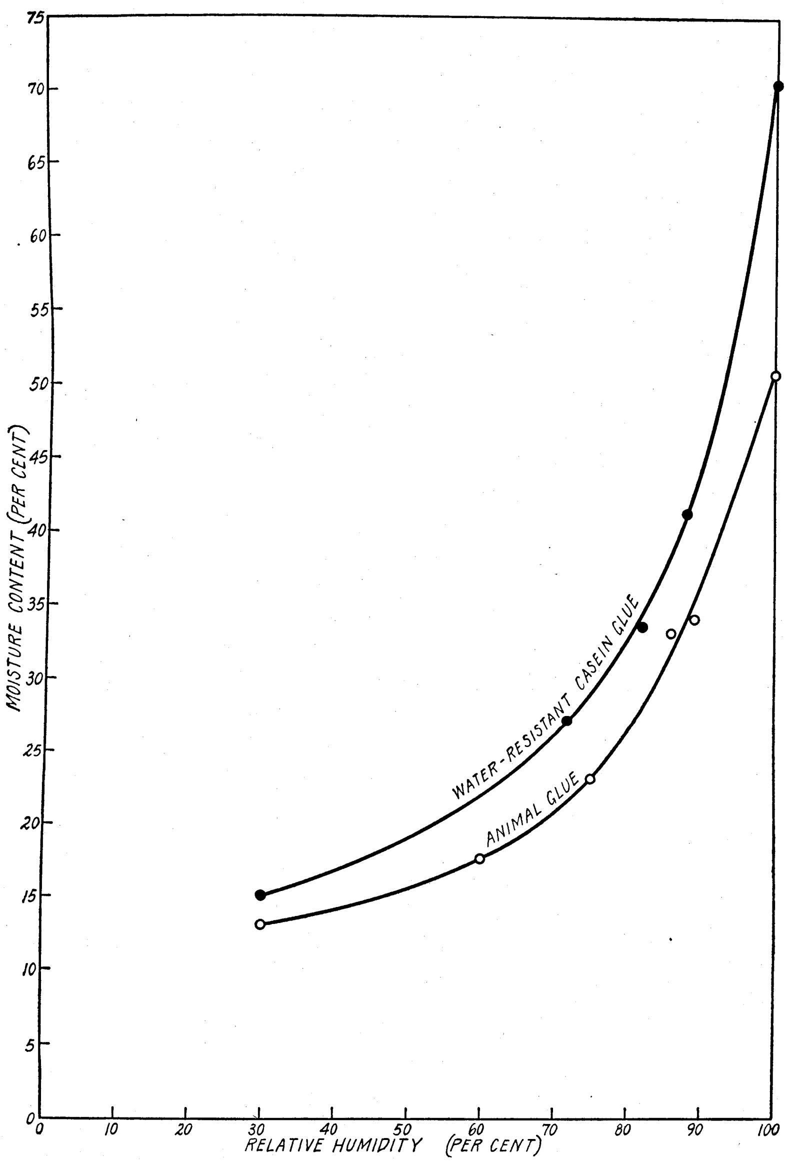

FIGURE 2.—Effect of relative humidity on moisture content of animal and casein glues suitable for aircraft. Tests made at 80° F.

VEGETABLE-PROTEIN GLUES

Soybean and peanut meal serve as bases for adhesives[7] which in general properties resemble casein glues. Some of them have a good degree of water resistance and are relatively cheap, but in their present stage of development they do not show so high a dry strength as the better quality casein glues.

PHENOL-ALDEHYDE CONDENSATION PRODUCTS

By heating a phenol with an aldehyde it is possible to produce hard, strong adhesive substances, which when set by hot pressing appear to be unaffected by moisture in any form. Nonaqueous solutions of these materials have been prepared that can be applied to wood. Tests of plywood glued with these products indicate very satisfactory joint strengths under all moisture conditions tried. Apparently phenol-aldehyde adhesives are more durable under extremely unfavorable conditions than the glues now used for woodworking, but their high cost has thus far practically prohibited their use. The necessity for hot pressing also restricts their application.

MISCELLANEOUS MATERIALS

Other materials, including cellulose cements, asphalts, resins, gums, and rubber have been tried as adhesives for wood. Cellulose cements have set very slowly in wood joints in tests at the Forest Products Laboratory and are otherwise difficult to use to obtain satisfactory adhesion. Likewise asphalts, resins, and gums have been tried out alone or in combination with other materials, but the results have not been entirely satisfactory. In their present forms these materials are not suitable as glues for aircraft joints, although they appear to have possibilities of development. Plywood has been glued by the hot-press process with an adhesive having rubber as its basic material. Joint tests of such plywood in both wet and dry condition indicate satisfactory strength. High cost is a present practical limitation affecting its use.

DURABILITY OF AIRCRAFT GLUES

None of the glues in practical use at present can be expected to form permanent joints in aircraft parts that are subject to prolonged saturation with water, such as seaplane hulls and floats, unless the glues or joints are especially treated. Even the most water-resistant blood-albumin or casein-glued joints, which show a strength when first saturated with water of 25 to nearly 100 per cent of their dry strength, fail completely when exposed without protection for a long time to free water or to extremely high atmospheric humidities. Failure in such cases is apparently caused by chemical decomposition of the glue or by its deterioration from the

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[7] The following patents relate to soybean and peanut-meal adhesives: JOHNSON, O. ADHESIVE. (U. S. Patent No. 1,460,757.) U. S. Patent Office, Off. Gaz. 312: 132. 1923; (Re 16,422). U. S. Patent Office, Off. Gaz. 350: 289. 1926. LAUCKS, I. F., and DAVIDSON, G. VEGETABLE GLUE AND PROCESS OF MAKING SAME. (U. S. Patents Nos. 1,680,732 and 1,691,661.) U. S. Patent Office, Off. Gaz. 375: 1136. 1928, and 376: 468. 1928. OSGOOD, G. H. GLUE. (U. S. Patents Nos. 1,601,506 and 1,601,507.) U. S. Patent Office, Off. Gaz. 350: 861. 1926. OSGOOD, G. H. WATERPROOFING VEGETABLE PROTEIN-BASE GLUE. (U. S. Patent No. 1,706,674.) U. S. Patent Office, Off. Gaz. 380: 875. 1929.

action of fungi and bacteria or perhaps both. Furthermore, unprotected water-resistant joints, which are known to withstand a limited number of soaking periods of several days each followed by drying out without seriously affecting their strength, fail eventually if subjected to a long series of large moisture changes by alternate wetting and drying. Under such cyclic conditions mechanical failure may be a factor in the breakdown of the joints in addition to chemical decomposition or the action of fungi.

Casein and blood-albumin glues, or even high-grade animal glues, do not deteriorate under conditions that produce about 12 per cent moisture content in wood, which is close to the average found in a survey of aircraft stations. (Table 2.) At such a moisture con-

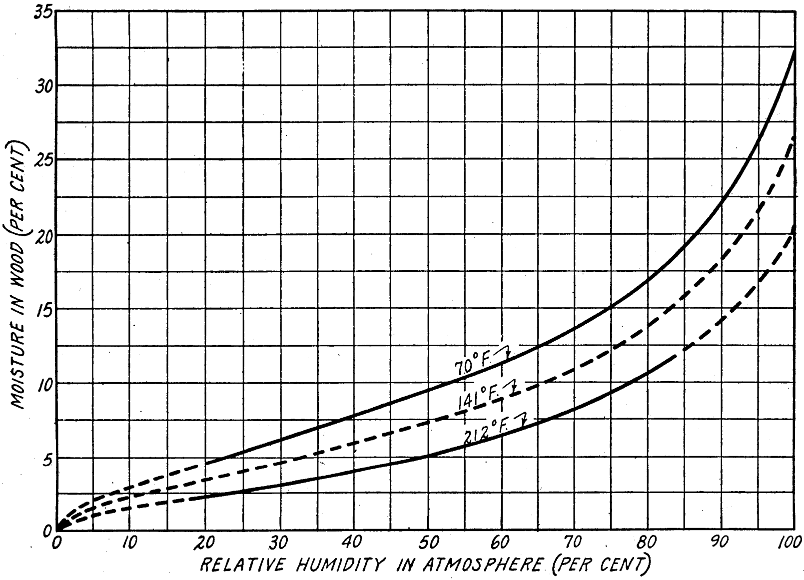


FIGURE 3.—Relation of the equilibrium moisture content of wood to the relative humidity of the surrounding atmosphere at three temperatures

tent, which is considered fairly representative, well-made joints of properly constructed members may reasonably be expected to remain permanent with only ordinary protection. Glue failures, however, are reported to occur in parts of aircraft under unusually adverse service conditions, where the moisture content of the wood undoubtedly exceeds the 12 per cent average considerably. Adequate data are not available for determining the exact critical moisture content at which casein or blood-albumin glues retain their strengths permanently and above which deterioration sets in. The available data indicate, however, that the critical range of moisture content is within 15 to 20 per cent for wood. Wood subjected to relative humidities of approximately 75 to 85 per cent and to a temperature of 70° F. takes on an equilibrium moisture content within this range. (Fig. 3.) Under conditions where the wood retains 20 per cent or more moisture there is no positive assurance of the permanence of glues without special treatment.

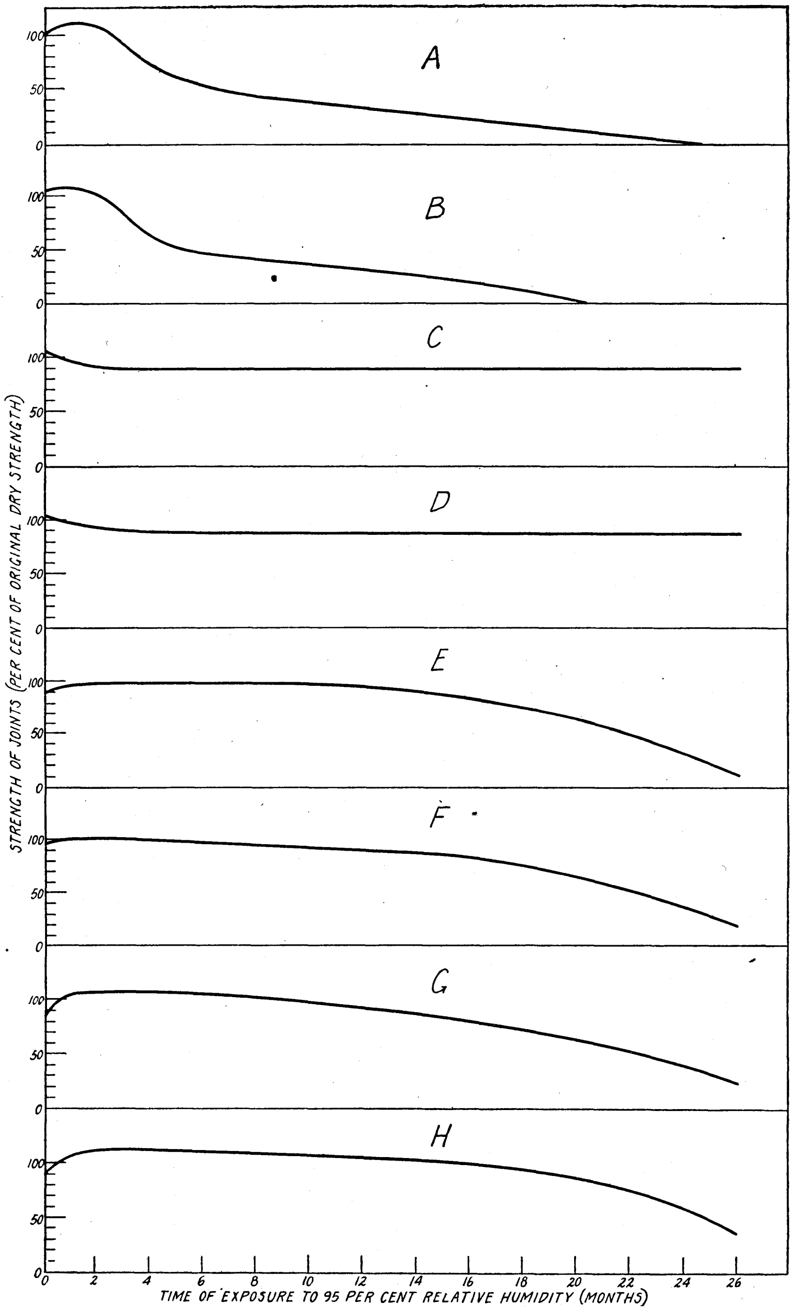
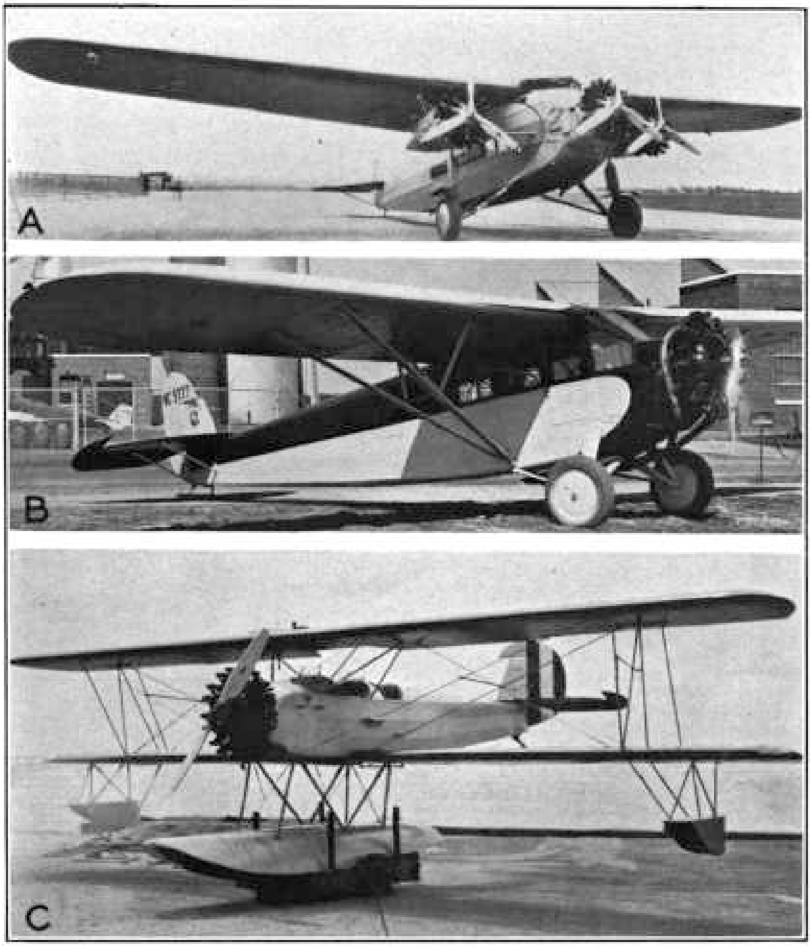
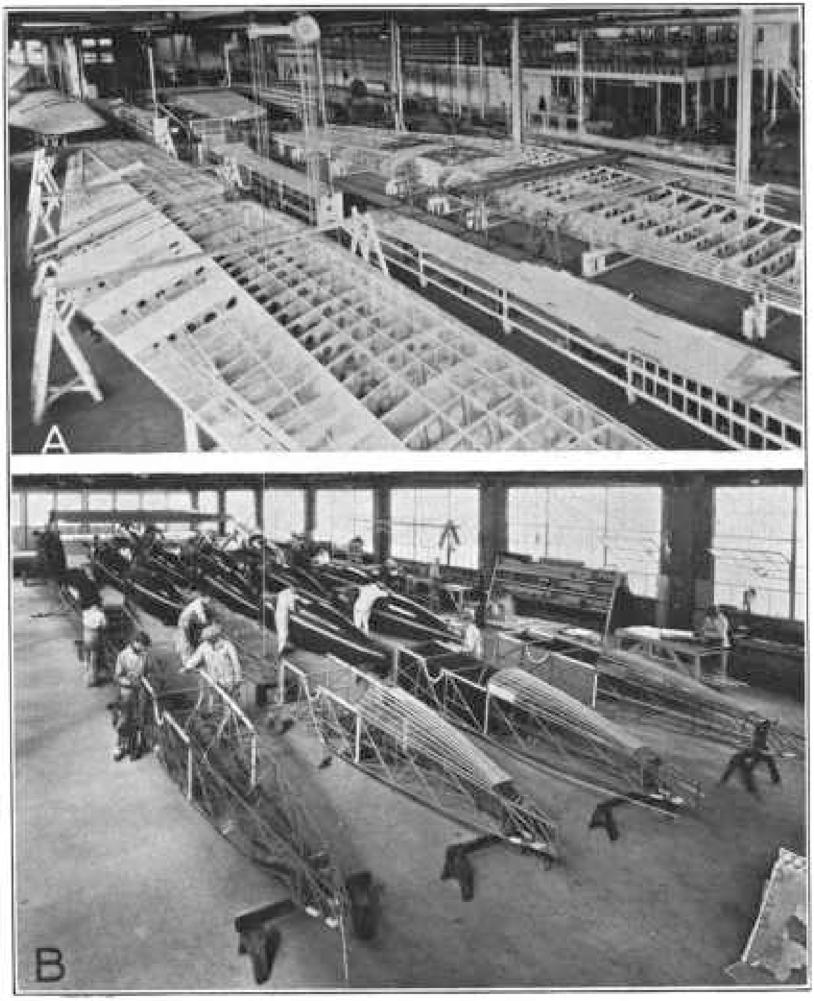


FIGURE 4.—Effect of treatment of casein glues and plywood joints on durability: A, Untreated; B, plywood specimens dipped in asphalt paint; C, plywood specimens treated with coal-tar creosote; D, plywood specimens treated with β naphthol in linseed oil; E, creosote added to glue before making joints; F, β naphthol added to glue before making joints; G, creosote added to glue and plywood specimens coated with aluminum powder in spar varnish; H, β naphthol added to glue and plywood specimens coated with aluminum powder in spar varnish. Joint strength tests made every month on 30 specimens for each treatment



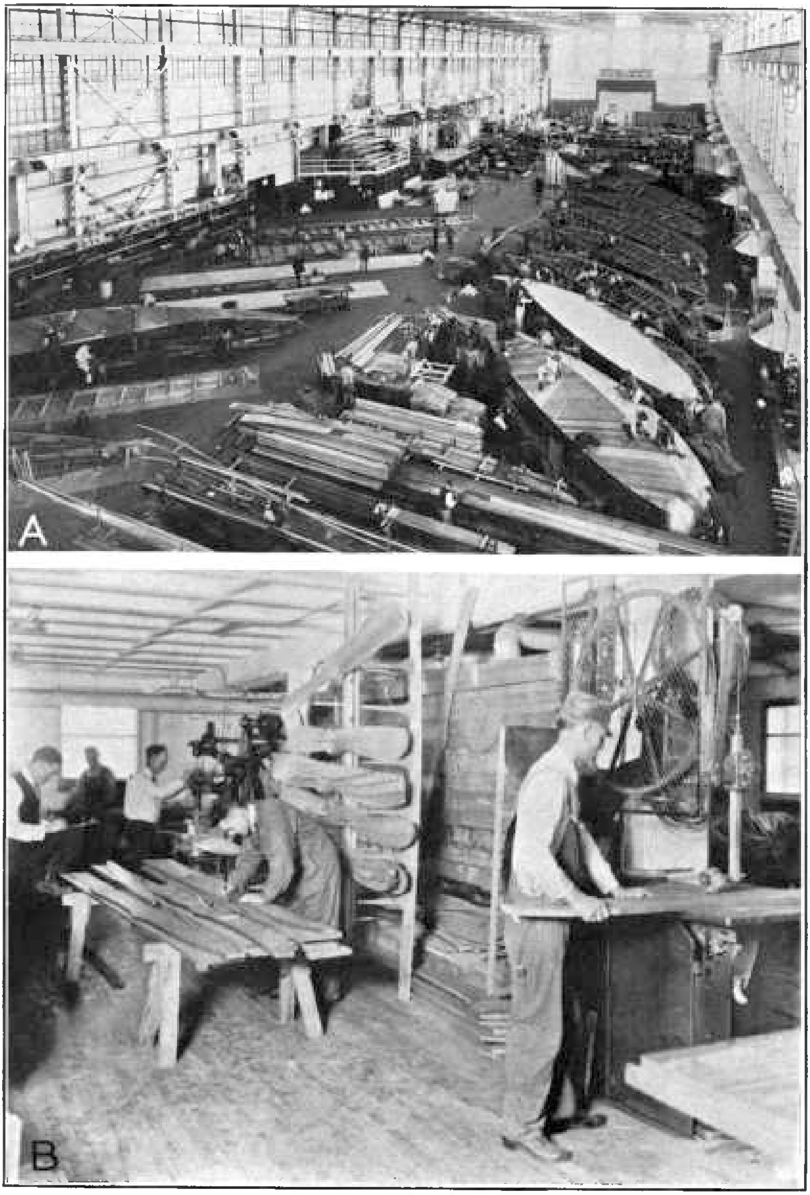
SOME TYPES OF COMMERCIAL AIRCRAFT EMPLOYING WOOD

A, 12-passenger monoplane in which the entire wing structure, including the covering, is made of wood. Wood is also used in part in the cabin construction; B, 6-passenger monoplane with framework and leading edge of wing and various parts of the fuselage made of wood; C, 2-passenger seaplane with wing structure, main float and wing tip floats constructed of wood.



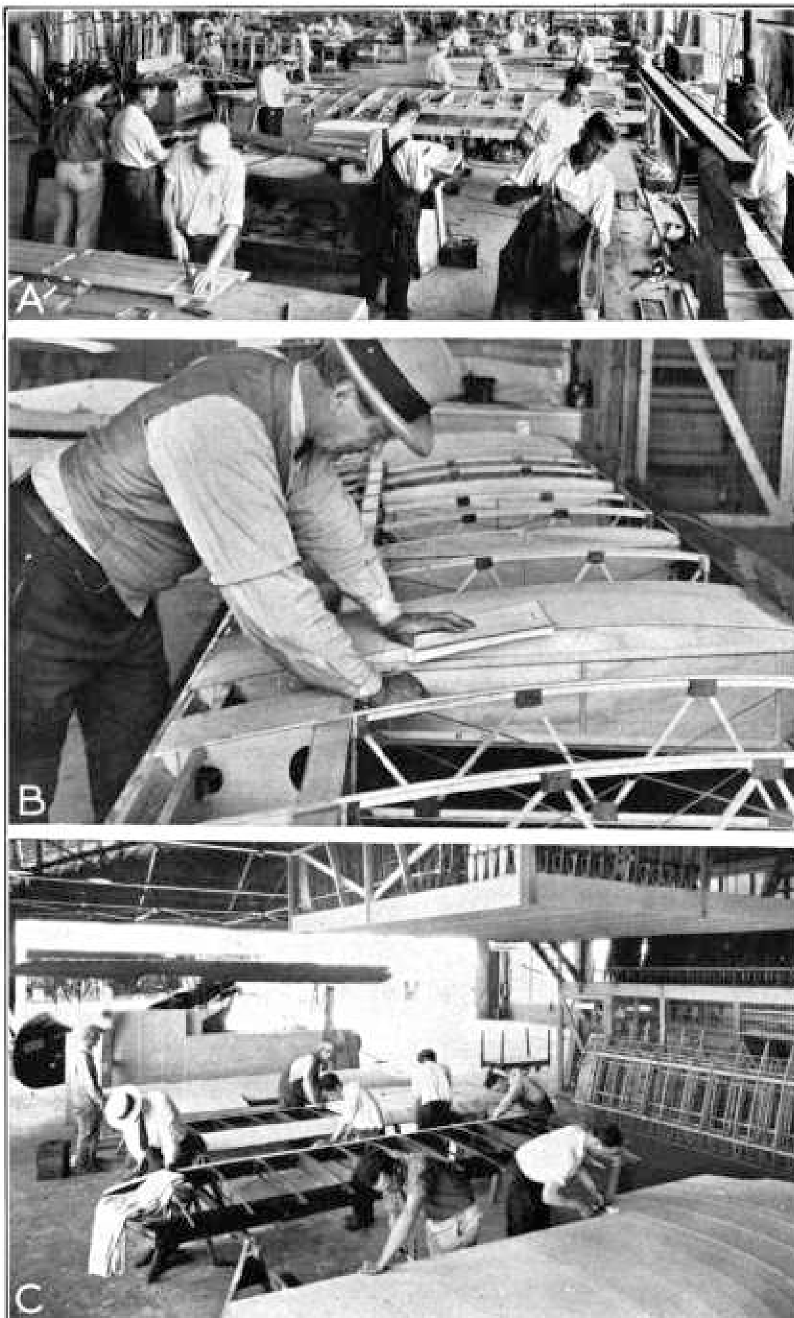
TYPICAL WOODWORKING DEPARTMENTS IN COMMERCIAL AIRCRAFT FACTORIES

A, Building wings entirely of wood for a large transport plane. The frame of the wing is covered with plywood; B, using wood for turtle decks and fairings in fuselages.



FLYING BOAT AND PROPELLER CONSTRUCTION

A, Constructing flying boat hulls of wood; B, manufacturing propellers of wood. Laying out and band sawing laminations preparatory to gluing.



WING BUILDING OPERATIONS

A, Making wooden wing structures for both biplanes and monoplanes; B, inspecting a wing structure before covering; C, covering wings with cloth.

TABLE 2.—*Moisture content found in wooden airplane parts under service conditions*

Kind of construction	Service	Stations where samples were taken [1]	Kinds of woods tested	Specimens tested	Moisture content—		
					Average for specimens tested [2]	Maximum for any one station and wood	Minimum for any one station and wood
		Number	*Number*	*Number*	*Per cent*	*Per cent*	*Per cent*
Solid and laminated wood [3]	Navy	10	10	419	12.7	15.3	8.8
Plywood	do	6	4	35	13.8	17.8	9.1
Solid and laminated wood [3]	Army	10	4	371	11.5	14.0	9.3
Propellers	do	9		75	10.3	11.3	8.4
Plywood	do	7		39	13.9	16.7	11.7

[1] Army and Navy stations are considered separately, although they are frequently located close to each other.
[2] Grand average for all stations where determinations were made; station averages were prorated on number of specimens tested.
[3] Exclusive of propellers.

INCREASING THE DURABILITY OF GLUED JOINTS

As a result of research work at the Forest Products Laboratory[8] special treatments of glues and joints have been discovered that materially increase the durability of glued joints under severe exposure. In Figure 4 are shown the results of a still incompleted series of prolonged exposure tests on casein-glued plywood. The results shown are based on two casein glues—one made in accordance with Forest Products Laboratory formula 4B (p. 54) and the other a special commercial aircraft glue. Because of the similarity of the results obtained with the two glues the data were averaged. The special treatments were of three general kinds; namely, (1) addition of preservative materials to the glues before making the joints; (2) preservative treatment of plywood that had been glued with untreated glues; and (3) treatment of glues before making joints, followed by the application to the glued joints of aluminum powder in spar varnish, which is an effective moisture-excluding coating.

In similar tests, blood-albumin glue was treated with sodium chromate and made into plywood. Ten per cent of sodium chromate proved to be effective in increasing the durability of the blood-albumin glue. Plywood, which had been made with untreated blood-albumin glue, was also treated either with *β* naphthol in linseed oil or with creosote. The treatment of the plywood specimens both with the *β* naphthol in linseed oil and with the creosote increased the durability of the joints. In one series of tests, plywood which had been glued with blood-albumin glue and treated with creosote after gluing, was exposed for four and one-half years in a moisture-saturated atmosphere without any appreciable loss in strength.

In applying special treatments to aircraft joints it is preferable to treat, as far as possible, complete assemblies, such as wing sections

[8] Tests were conducted in cooperation with the National Advisory Committee for Aeronautics.

and floats (pls. 5 and 7, A) before covering. It is recommended that the assembled parts be dipped in a hot bath of boiled linseed oil containing 25 per cent of *ß* naphthol[9] or in coal-tar creosote. Better protection will be afforded by dipping the member first in a hot bath, about 200° F., and then in a cold bath, allowing the member to remain about one-half hour in each. The linseed oil and *ß* naphthol mixture is mushy at ordinary room temperatures and the "cold bath" must be kept at about 150° to obtain proper absorption and to prevent the formation of a thick layer on the surface of the wood. The weight of the member will be increased somewhat more with the increased temperature and with the time it remains in the baths. The weight added in a treating process will depend also upon the size and shape of the members. Small pieces having large surface areas in proportion to their volume, such as the specimens used in the tests on which Figure 4 are based, will have more weight added per unit volume than large, compact parts.

The foregoing treatments are distinctly superior to the present methods of dipping, spraying, or brushing with varnish or asphaltic materials. Applying the preservative to the glue alone will increase the weight of the member only slightly and, although not so effective as treating the whole member, it may give sufficient protection for certain aircraft parts exposed under average conditions of use.

TESTING GLUES FOR QUALITY

Due vigilance should be exercised to see that glues for use in aircraft conform to standard specifications or requirements. Specifications for glues and glue materials are valuable both as a guaranty of quality and as a means of obtaining more uniform results in use.

No attempt is made in this publication to describe acceptance tests in detail, since the published literature pertaining to the subject is ample and readily available[10] (*25*, *11*, *6*, *27*).

TESTS FOR CASEIN GLUE

Joint tests constitute at present the principal means for judging the value of casein glues for use in aircraft. Considerable time is required to make joint tests. Moreover, they are difficult to perform accurately, and at best yield only indirect comparisons of glue properties. On the other hand, joint tests, when properly carried out, afford highly important information about the value of the glue in service and its adaptability to manufacturing conditions.

Block shear and plywood tests for joints have been adopted as standard by the Army and Navy. Except for certain changes as to the form of specimen and shearing tool used in the block shear test and the method of measuring water resistance in the plywood test,

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[9] The treatment here recommended is the same as used on the plywood specimens indicated in Figure 4. The minimum amount of *ß* naphthol, which will properly protect the glued members is not known.

[10] Detailed information on U. S. Army and Navy acceptance tests are contained in United States Army, Glue, Casein, Specif. No. 98–14020–D, 5 p., illus, 1926; United States Army, Glue, Hide, Specif. No. 3–140, 3 p., 1927; United States Navy, Glue, Casein. Dept. Specif. No. 52G8, 5 p., illus., 1924; and United States Navy, Glue, Hide, Dept. Specif. No. 52G4C, 2 p., 1925.

the details of the two tests are substantially the same as those originally worked out by the Forest Products Laboratory (*1*). The form of test specimens, shearing tool, and grips used at present at the laboratory are shown in Figures 5 and 6. Water resistance is now measured at the laboratory and by both the Army and the Navy by testing plywood specimens wet after soaking in cold water for 48 hours, whereas originally the only requirement was that plywood show no separation of the plies after soaking in hot or cold water.

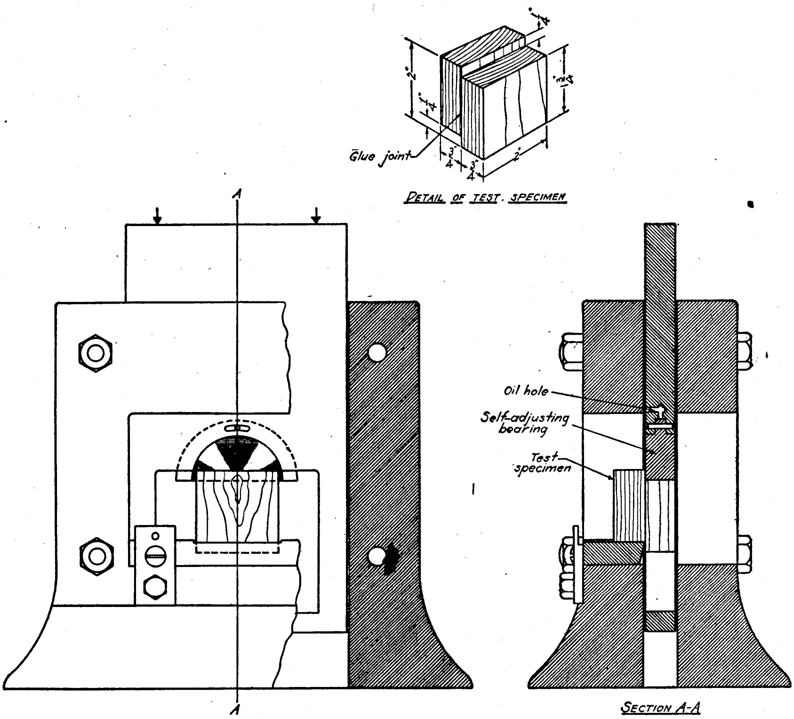

FIGURE 5.—Specimen and shearing tool used at Forest Products Laboratory for block-shear joint test. Experience has shown that it is necessary to conform strictly to the details shown in order to obtain comparable results

Experience has shown that the following points are important in making joint tests:

BLOCK SHEAR JOINT TEST

(1) Select a wood (hard maple is satisfactory), which glues well, is high in density, of straight grain, and free from defects. Condition to a uniform moisture content of about 7 per cent.

(2) Glue the joints large enough that four or more specimens (fig. 5) can be cut from each joint; also test two or more joints for each glue.

(3) Surface the wood pieces smoothly and to a uniform thickness immediately before gluing.

(4) Follow directions carefully in preparing glue for use.

(5) Spread approximately 1¼ ounces of wet glue evenly to each square foot of joint and apply pressure uniformly to the surfaces when the glue is at the proper consistency. (P. 24 for details.)

(6) Allow the glue to set under pressure for 15 hours or more and then condition joints to a uniform moisture content of approximately the same as

before gluing. (Seven days' conditioning time at room temperature is usually sufficient.)

(7) Prepare specimens of the type shown in Figure 5, and test on a testing machine equipped with a shearing tool as shown also in Figure 5. Apply the load to the specimen at a rate not greater than 0.0157 inch per minute.

(8) Record for each specimen both the breaking load and the approximate percentage of wood failure occurring over the glue-line area.

(9) Whenever a specimen fails with a load less than the required average [11] and the failure occurs 50 per cent or more in the wood, the specimen should be rejected in computing the average. If the variation among individual specimens is 10 per cent or more and the breaking strength of one or more specimens is equal to or higher than the required average strength, the test should be repeated.

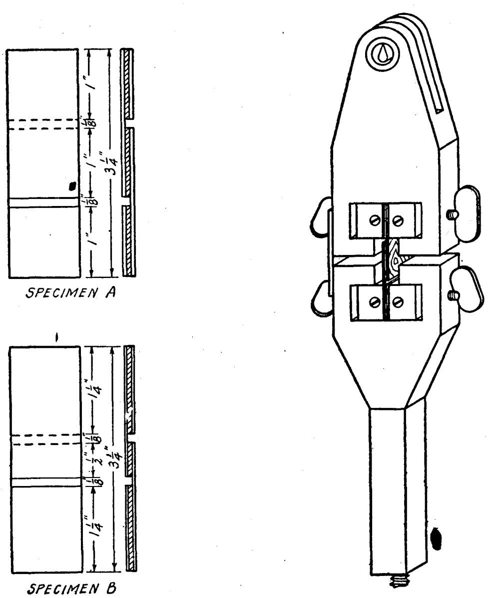

FIGURE 6.—Specimens and grips used at Forest Products Laboratory for plywood joint test. Experience has shown that it is necessary to conform strictly to the details shown in order to obtain comparable results

PLYWOOD JOINT TEST

(1) Use a strong wood (yellow birch is quite satisfactory).

(2) Select veneer that is straight grained, comparatively free from checks, smooth, uniform in thickness, and free from other visible defects. Results obtained from specimens with cross grain through the face plies and with badly checked cores do not represent the full strength of the joint and should be disregarded in testing the quality of glues.

(3) Use, where possible, a standard construction. Three plies, each one-sixteenth of an inch thick, glued with the grain of the core at right angles to the faces, are generally used.

(4) Condition all veneer to approximately the same moisture content before gluing. It is recommended that the moisture content be not higher than 12 nor lower than 7 per cent.

(5) Prepare glues for use in accordance with manufacturer's directions.

(6) Glue the plywood under carefully controlled conditions. (P. 35 for details.)

(7) Leave the panels under pressure for at least 15 hours and then condition them to approximately the same moisture content that the veneer had before gluing. Three days' conditioning is usually sufficient.

(8) Cut specimens as shown in Figure 6. Where the face plies do not withstand the loads under test with specimen A, the shearing area should be reduced to one-half square inch as shown in specimen B.

(9) Use care in placing specimen in machine and adjusting the grips. (Fig. 6.) Apply the load to the specimen at a rate of 600 to 1,000 pounds per minute.

(10) Record both breaking load and nature of failure.

(11) Test an equal number of specimens dry and wet from each panel and preferably four or more panels for each glue.

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[11] The average breaking strength required by the U. S. Navy Dept. Specif. No. 52G8 (1924) and the U. S. Army Specif. No. 98–14020–D (1925) is 2,400 pounds per square inch. If the test is carefully performed several available high-grade casein glues give joint strengths considerably in excess of 2,400. At the Forest Products Laboratory a number have exceeded 2,800 pounds per square inch.

(12) In case a specimen fails with a load per square inch less than the required average strength[12] and the failure occurs 50 per cent or more in the wood, the specimen should be disregarded in computing the average.

Plywood made of different thicknesses of veneer will give different values when tested in the manner shown in Figure 6. This is because of the form of specimen, its tendency to bend, and the eccentric loading which occurs under test. The test values vary with the thickness of both the face and core plies, and the order of magnitude

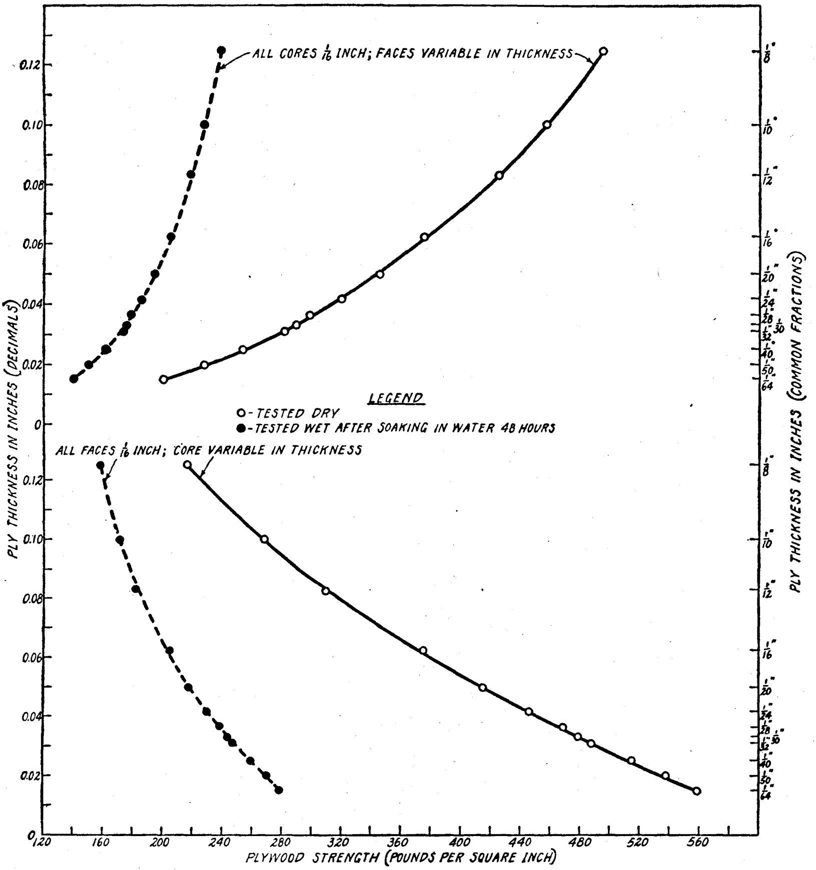


FIGURE 7.—Effect of ply thickness on strength values obtained in plywood test

of these variations is shown in Figure 7. It is important, therefore, that a standard construction be used in making tests on glues.

In addition to joint tests casein glues are sometimes tested to determine their working life. Highly water-resistant casein glues, when mixed ready for use, thicken after a time, usually within a few hours, to a jelly and become unusable. The working life is considered as the period in which the glue mixture remains in a satis-

[12] U. S. Army Specif. No. 98–14020–D (1926) and U. S. Navy Dept. Specif. No. 52G8 (1924) require an average of 250 pounds per square inch tested dry and 125 pounds per square inch tested wet after soaking in water at room temperature for 48 hours.

factory consistency for spreading on wood. A requirement of four to five hours' working life is reasonable. It must be remembered, however, that some thickening will occur during this period. A glue that does not thicken and set eventually to a firm jelly is almost certain to be low in water resistance, even though the mixture is used while fresh (p. 3). Hence the working-life test is valuable not only as a measure of the time during which the glue remains in a satisfactory condition for use but as a rough check on its water resistance. It seems possible that consistency and jelly strength tests in addition to determining the working life of casein glues may eventually be used to measure certain of their mechanical properties (4).

TESTS FOR BLOOD-ALBUMIN GLUES

The blood-albumin glues used in the manufacture of aircraft plywood are mixed by combining the various ingredients at the time of use. The aircraft manufacturer is not concerned with the testing of blood-albumin glues directly since this class of adhesives is used chiefly in gluing plywood, most of which is made in plywood manufacturing plants. Joint tests are the principal means by which blood-albumin glues are evaluated. The plywood test described for casein glues (p. 12) can also be used for blood-albumin glues.

TESTS FOR ANIMAL GLUE

The viscosity and jelly strength of specified concentrations of solutions, tested at definite temperatures, are at present the principal criteria of quality in animal glues. For proper execution these tests require careful control of conditions, accurate measuring apparatus, and a trained observer. In general, the higher the viscosity and jelly strength, considered jointly, the better the strength and general serviceability of the glue. Either one of the two tests without the other may yield a fictitious indication for a given glue.

The adoption of standard methods and equipment will greatly simplify the testing of animal glues and largely overcome the confusion which has existed in the past. The National Association of Glue Manufacturers has worked out and adopted a uniform system of testing and grading glues based on the viscosity and jelly strength, which promises to bring about a very desirable simplification (*5*).

The jelly point of an animal glue is the temperature at which a solution of the glue changes from a liquid to a jelly. It determines in large part the necessity for warming the wood and is therefore of considerable importance in the shop. As an acceptance test, however, it is doubtful whether the jelly point reveals any service quality of the glue not indicated by viscosity and jelly strength. No standard method for determining the jelly point has yet been agreed upon, but an approximation can be easily obtained by cooling a portion of glue solution and noting the temperature at which it ceases to flow.

A number of other properties of animal glues are of practical importance. Acidity or alkalinity, tendency to foam, odor and keeping quality, and amount of grease and other extraneous materials present all determine to a greater or less extent the fitness of a glue for high-grade joint work as required in aircraft. The first three of these properties can be determined comparatively easily within the limits required of a glue for joint work and should be made a consideration in selection. The presence of grease and other foreign materials in small amounts is not particularly objectionable, and the exact percentages can be determined only by quantitative analyses, which would hardly be justified under all conditions. The amount of moisture present should be taken into consideration in the preparation of solutions for the viscosity and jelly strength tests.

PREPARATION OF GLUES FOR USE IN AIRCRAFT

Clean, cold water should be used with the glues that are under consideration in this bulletin, and the quantity of dry glue and water should be determined by weight rather than measure or guess. The aim in mixing glues should be to produce a solution of the proper consistency and free from air bubbles, foam, and lumps of undissolved material. Machine mixing normally produces a more thoroughly mixed glue than stirring by hand.

PREPARING CASEIN GLUE

Casein glues suitable for use in aircraft are of two kinds, those prepared in dry form ready to be added to water and those in which the various materials are combined at the time of mixing with water. The first are generally referred to as "prepared" glues and the second as "wet-mix" glues. Both kinds are mixed without heating and in the same type of equipment. Various types of mixers have been used successfully, but the dough type (pl. 8, A and B), equipped with a mechanism for turning the paddle in a double rotary motion at two or three different speeds, has been quite generally used with excellent results. The chief requisites of a mixer for casein glues are (1) thorough agitation, preferably with different speeds of the paddle, and (2) a bowl that can be readily removed from the machine for cleaning, made of some metal that will not corrode rapidly from the action of alkali.

In aircraft repair shops in which only small quantities of glue are needed the mixing may be done by hand, but this is recommended only where machine stirring is not feasible. A small mixer of the type shown in Plate 8, A and B may be procured, equipped with two sizes of mixing bowls in which quantities of wet glue varying from 2 to 20 pounds may be mixed successfully. Where hand stirring is necessary a paddle or stiff spatula should be used. Egg beaters may be used but unless operated at low speed they have a tendency to stir in air and thus produce a foamy mixture. The conditions and procedure recommended in succeeding paragraphs for mechanical mixers should be approximated as nearly as possible in hand mixing.

A survey of aircraft-gluing operations (*22*) has shown that various types of mixers are in use with varying results. Drill presses, to which are attached a small, homemade paddle or stirrer are used in a number of plants. These are usually run at too high a speed and cause a foamy mixture. Furthermore, the stirrer does not agitate the mixture uniformly, and lumps are apt to form while the dry glue powder is being added. Other 1-speed mixers now in use frequently permit lumps to form or whip air into the mixture. For these reasons the use of a 2-speed mixer, equipped with a stirrer large enough to agitate the whole mixture uniformly at speeds of 100 to 120 and 50 to 60 revolutions per minute, respectively, will improve the mixing in many aircraft factories.

The correct proportion of glue and water varies with the particular brand of glue and somewhat with the type of joint. Manufacturers usually recommend the proportions of glue and water, and these should be followed unless other proportions are known to give better results. For most prepared casein glues a ratio of 1 part of glue to 2 parts of water (by weight) gives a proper consistency for side-grain joints. For wet-mix glues the proportions of water and other ingredients are given in the formulas in the appendix. For gluing end-grain joints some variation in the glue-water ratio is necessary as described on page 45.

With prepared casein glues the dry powder is simply mixed thoroughly with the water and stirred until it has dissolved. The water should first be placed in the bowl of the mixer and the glue sprinkled or sifted in slowly with the paddle in rapid motion. Care should be used that large lumps do not form. After the dry glue has all been added the motion of the paddle should be slowed down, but the stirring should be continued (usually 20 to 30 minutes) until a smooth mixture of even consistency results. Variations in procedure are advisable for certain prepared casein glues. In such glues the glue-water proportions and other details are usually recommended by the manufacturer.

Wet-mix casein glues are prepared according to formulas by the addition of the separate ingredients at the time of mixing. Detailed directions for mixing casein glues suitable for aircraft work are given on pages 52 and 54.

The prepared glues are convenient and easy to mix, while the wet-mix glues require somewhat more attention and skill in mixing. With either glue, however, a procedure can easily be acquired for mixing the various ingredients which the average man can follow without difficulty.

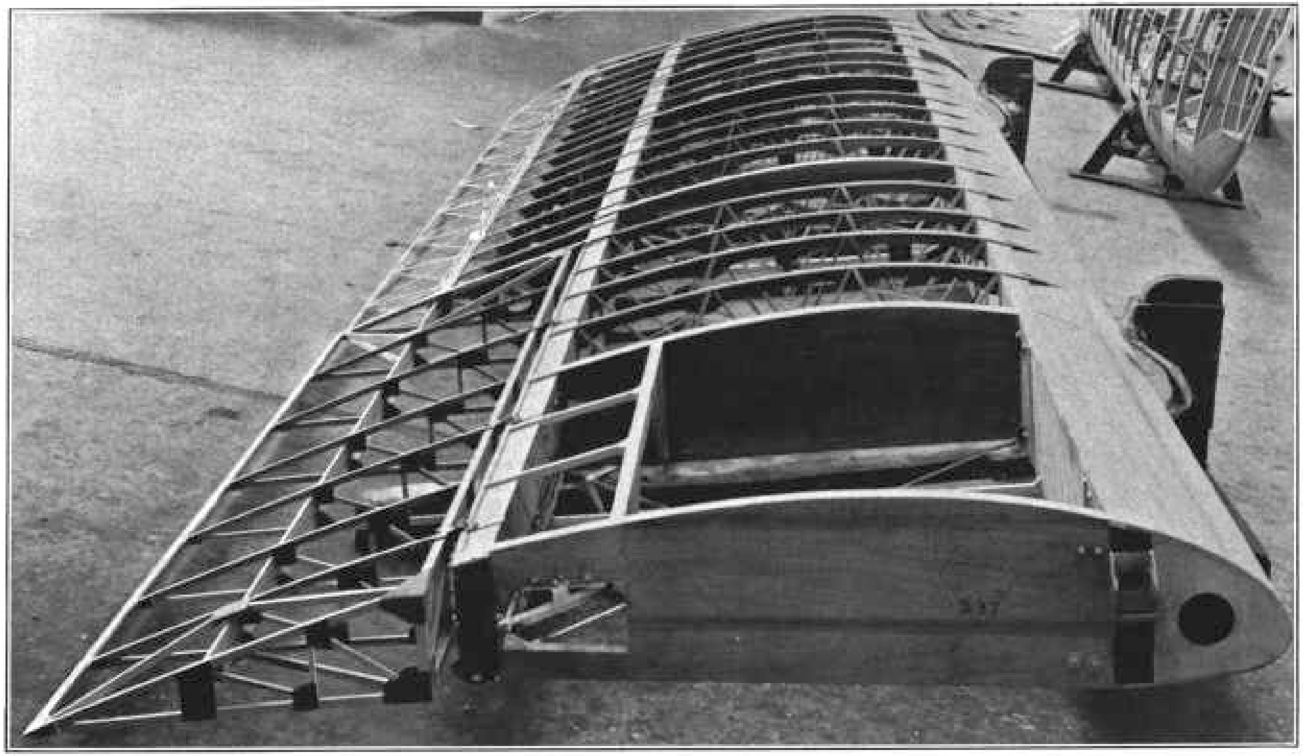
Most water-resistant casein glues become noticeably thicker on standing at room temperatures, but in such cases the quality of joints apparently is unaffected so long as the glues can be applied satisfactorily. On the other hand, casein glues that do not set to a jelly until a long time after mixing frequently become thinner; such thinning action usually indicates a deterioration of the glue, which may render its use unsafe. In general, mixtures that remain liquid for a long time do not produce joints of high water resistance, such as required in aircraft, even though the mixture is used while fresh.

Mixers, spreaders, and other equipment used with casein glues should be thoroughly cleaned at regular intervals to prevent deterioration of the glue and the inclusion of pieces of dry glue in the freshly prepared mixture. A thorough cleaning every working day, before the glue hardens, is highly desirable.

PREPARING ANIMAL GLUE

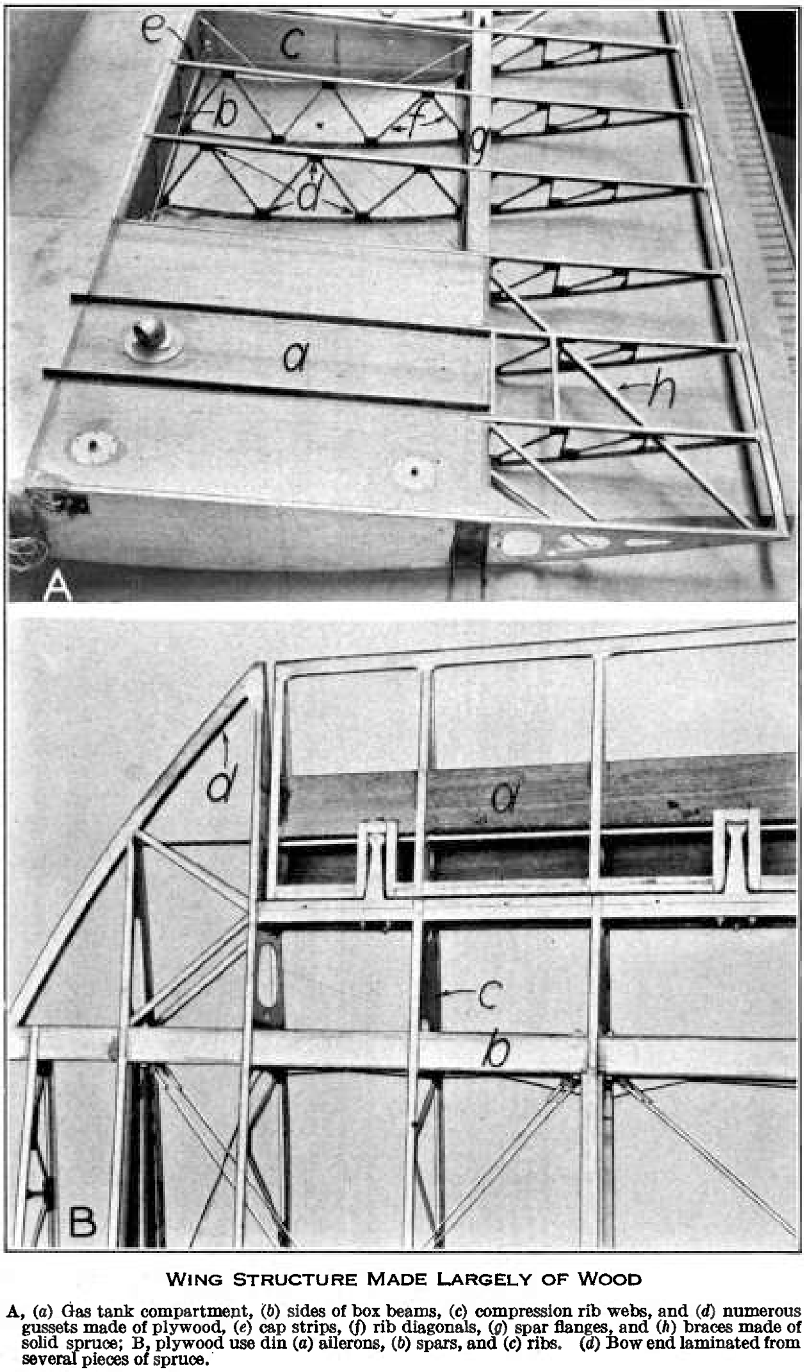
An animal glue which meets aircraft specifications [13] requires for each pound of dry glue about 2¼ pounds of water for standard side-

[13] Specification No. 3–140 (1927) of the U. S. Army and No. 52G4C (1925) of the U. S. Navy cover animal glue for use in aircraft.



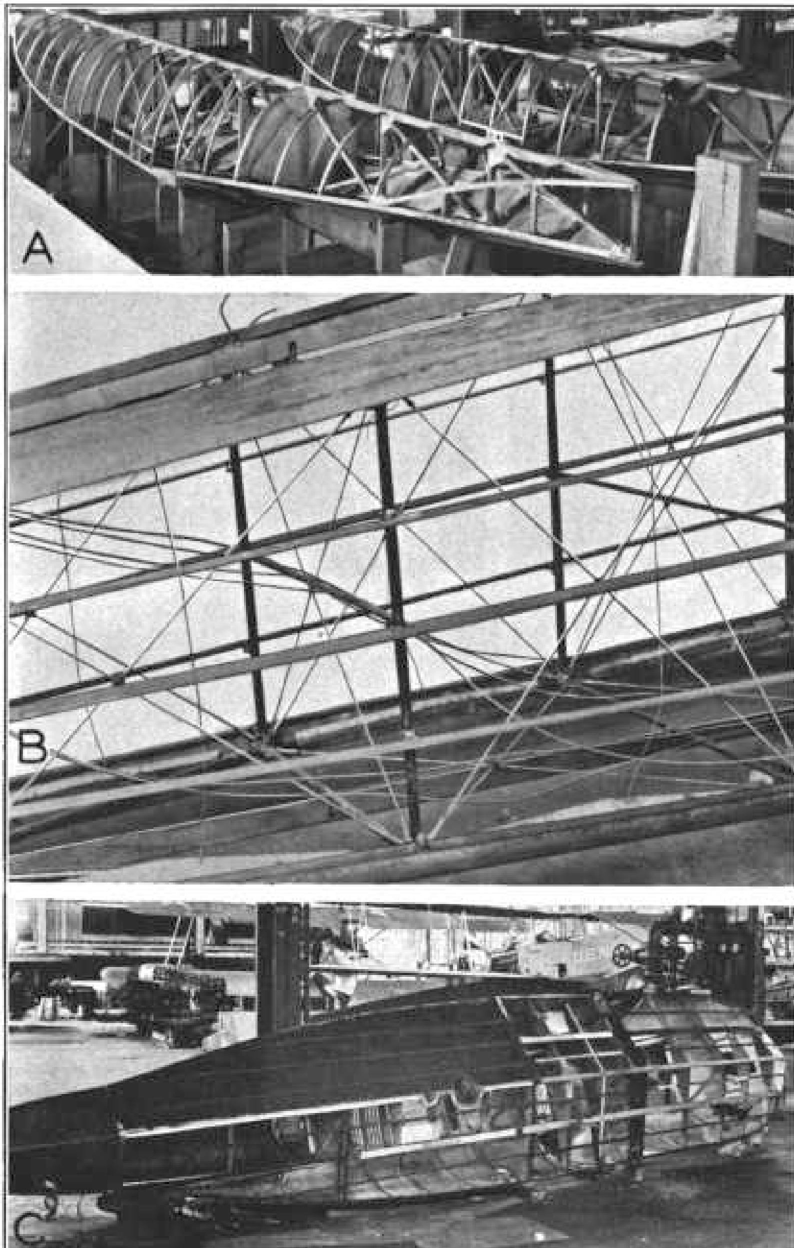
THE STRUCTURE OF A HALF MONOPLANE WING

This part of the wing, except the aileron, is made of wood. Its construction requires the making of more than 1,000 glued joints. Note the many small pieces of spruce and the use of plywood for the sides of the gas compartment, the sides of the box beams, the leading edge, the webs of the ribs, and the gussets.



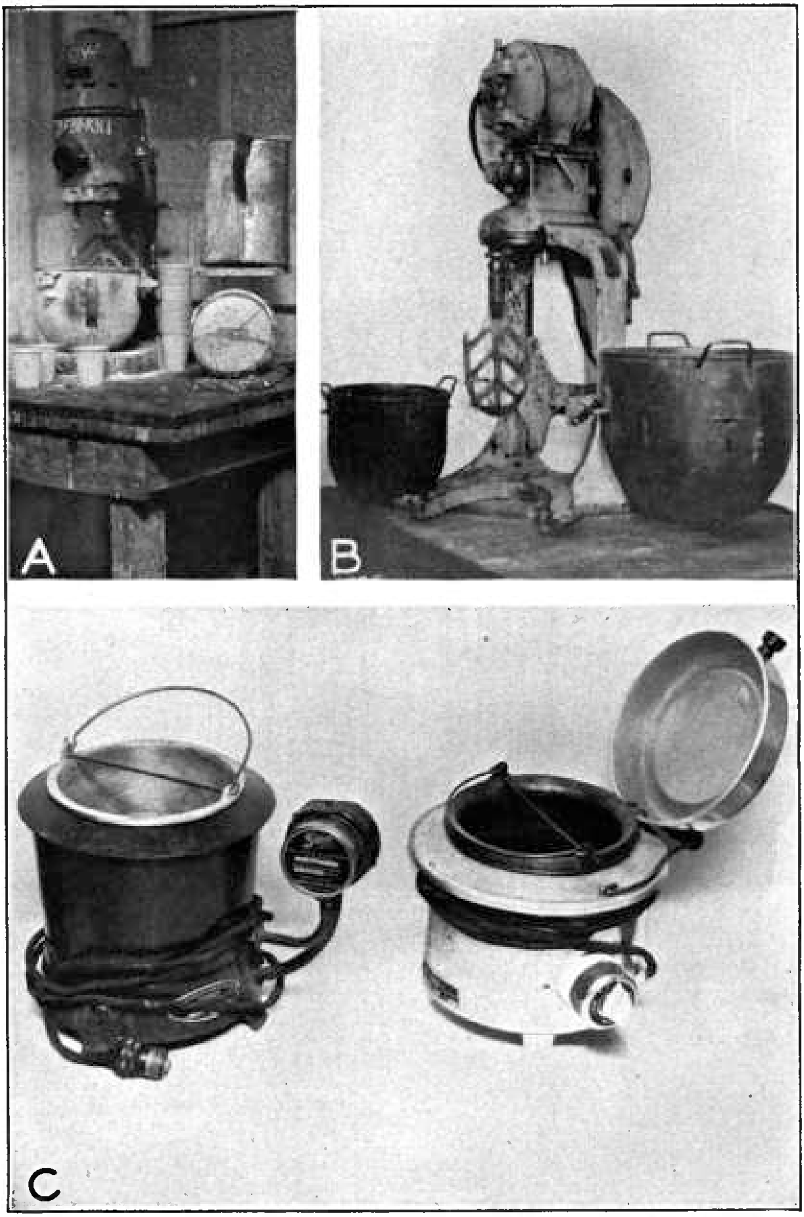
WING STRUCTURE MADE LARGELY OF WOOD

A, (*a*) Gas tank compartment, (*b*) sides of box beams, (*c*) compression rib webs, and (*d*) numerous gussets made of plywood, (*e*) cap strips, (*f*) rib diagonals, (*g*) spar flanges, and (*h*) braces made of solid spruce; B, plywood use din (*a*) ailerons, (*b*) spars, and (*c*) ribs. (*d*) Bow end laminated from several pieces of spruce.



WOOD IN PONTOON, FUSELAGE, AND AMPHIBIAN CONSTRUCTION

A, Pontoon frames made largely of wood. The curved ribs are of thin laminated construction; B, wood is used on the frame of fuselages as a base to which is attached the covering and various accessories. Seats, floors, instrument boards, bulk heads, and other parts are also made largely of plywood; C, wood and plywood used in the construction of an amphibian hull.



SATISFACTORY MIXING EQUIPMENT FOR CASEIN AND ANIMAL GLUES

A, 2-speed, 5-quart size, electric, casein glue mixer in use in an aircraft factory. The dry glue and water are weighed on the scale and the mixed glue is distributed to the workmen in the small paraffined paper cups; B, 3-speed dough-type, electric mixer, equipped with 3 and 8 quart howls and two sizes of paddles for mixing casein glue; C, two types of electric glue pots with automatic temperature control for animal glue.

grain gluing. This proportion may be varied to 1 part glue to 2 parts water where a mixture of a heavier consistency is required, as on end-grain surfaces or in quick pressing operations and on warm wood. On the other hand, a mixture of 1 to 3 may be used for sizing purposes.

The following recommendations are made for the preparation and handling of animal glue for aircraft work: (1) Soak glue in clean, cold water until all particles are softened.[14] Mix thoroughly the glue and water when combining so as to insure uniform absorption; (2) melt glue in a heater from which the solution may be removed as soon as melted or in which the temperature can be accurately controlled (pl. 8, C); (3) keep the melted glue at a temperature between 140° and 150° F.; (4) use the glue as quickly as possible after melting. Glue that has been heated for a total time of four hours should be discarded;[15] (5) clean thoroughly all glue receptacles at least once during each working day.

PREPARING BLOOD-ALBUMIN GLUES

Blood-albumin glues are prepared by combining the several ingredients at the time of mixing. Dried soluble blood albumin is generally used. The proportions of water and other materials added to the dried blood albumin vary greatly with different formulas. Two blood-glue formulas developed at the Forest Products Laboratory, with detailed directions for mixing, are given on page 54.

In general blood glues, used commercially, are prepared in accordance with secret formulas and processes. Most formulas are reported to have originated in European and Asiatic countries where blood glues have been used for a longer time and more extensively than in this country. The mixtures of most value for aircraft are of a viscous, or noncoagulated type, and have a comparatively low water content.

The working life of blood glues is extremely variable, depending chiefly upon the proportions of alkali and water added to the dried albumin. Glues can easily be mixed that have a working life of several hours to a day or more. As with other glues made from animal material, precautions should be taken to prevent deterioration from bacteria and other organisms of decay.

PREPARATION OF WOOD FOR GLUING

MOISTURE CONTENT

Wood for gluing should have the proper moisture content, uniformly distributed throughout, and should be free of casehardening and other stresses (*21*).

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[14] The time required to soften the glue thoroughly may vary from one to several hours. One hour is sufficient time for a ground glue that will pass an 8-mesh screen. Longer periods are required for coarsely ground and flake glues. Glue which is soaked for several hours should be placed in a refrigerator at a temperature of about 40° to 50° F. to prevent deterioration.

[15] Batches of mixed animal glue may be kept from one day to the next at a temperature of 40° to 50° F. without any appreciable deterioration and remelted and used later with safety. The batch should be discarded, however, when the combined heating periods total four hours. Dry glue will keep for an indefinite period at ordinary room temperatures if safeguarded from dampness.

Any considerable change of moisture content in wood after gluing usually develops stresses in the glue and reduces the load that the member will withstand in service. The ideal moisture relation to be aimed at in gluing for maximum joint strength, therefore, is that the moisture content of the wood at the time of gluing plus the moisture added by the glue should be equal to the average moisture content that the member will have in service. In Table 2 are shown the average maximum and minimum moisture-content values of wood in service in airplane parts, as determined at various aircraft stations throughout the United States. Table 3 shows the approximate percentages of moisture added to wood by the glue in certain types of construction.

The effect of a different moisture content of the wood, before and after gluing, on the joint strength of casein-glue plywood is illustrated in Figure 8. The plywood for the wet tests was soaked in cold water for 48 hours and tested in the saturated condition. The dry tests were made at a moisture content of 10 to 12 per cent.

TABLE 3.—*Percentages of moisture added to wood in gluing*[1]

Construction	Plies or laminations	Species and thickness of— Faces	Crossbands	Core	Laminations	Nominal total thickness	Moisture added by glue[2]
	No.					*In.*	*P. ct.*
Plywood	3	1/48-inch, yellow birch.		1/48-inch, yellow birch.		1/16	48.8
	3	1/32-inch, yellow birch.		1/32-inch, yellow birch.		3/32	32.5
	3	do		1/16-inch, yellow poplar.		1/8	29.6
	3	1/20-inch, Honduran mahogany.		1/10-inch, Honduran mahogany.		3/16	19.6
	5	1/28-inch, yellow birch.	1/20-inch, yellow poplar.	1/20-inch, yellow poplar.		7/32	36.1
	5	1/20-inch, yellow birch.	do	do		1/4	30.9
	5	1/16-inch, yellow birch.	1/12-inch, yellow poplar.	1/12-inch, yellow poplar.		3/8	21.2
	7	do	do	do.[3]		1/2	23.1
Laminated	15	do.[4]		do.[3]		1	23.4
	7				1/8-inch, Sitka spruce.	7/8	17.3
	10				3/4-inch, white oak	7 1/2	1.7
	2				1-inch, white ash	2	.8

[1] Percentages calculated from average weights (oven dry based on volume when air dry) of various species as given in Table 3 of Report No. 84 of the National Advisory Committee for Aeronautics (*7*) or Table 2 of U. S. Department of Agriculture Bulletin 556 (*19*). In the calculations it is assumed that all the surplus moisture added by the glue is absorbed by the wood. This assumption is known to be somewhat in error, but it nevertheless affords a fairly satisfactory basis for comparison.

[2] A glue mixture of 1 part dry glue and 2 parts water and a spread of 40 square feet of single glue line per pound of dry glue is assumed in this calculation.

[3] Core consists of 3 plies.

[4] Outer 12 plies all of same species and thickness.

From these data it might seem that the proper moisture content of wood at the time of gluing is an extremely variable quantity, depending upon the high or low moisture content of the finished article in service and the exact thickness and other characteristics of stock being glued. In general practice, however, adjustments can not be made for all such widely varying factors. Experience has shown that a moisture content of 5 to 10 per cent is satisfactory for veneer and thin laminations that are to be glued into plywood and laminated construction, respectively, provided all plies or laminations are at approximately the same moisture content within this range. For laminations one-half inch thick and thicker, a moisture content of 10 to 12 per cent is recommended, except for propellers. Propellers are commonly coated with an effective moisture-resistant finish, so that a moisture content of about 8 per cent before gluing is recommended. Wood for aircraft seldom must be conditioned to a moisture content as low as 5 per cent or higher than 12 per cent. Under average aircraft-manufacturing conditions a range of moisture content from 7 to 12 per cent is the most easily obtained and maintained and will ordinarily prove satisfactory for most veneer and lumber.

The moisture content of wood that has been properly dried for gluing may change in storage or in the factory during manufacture,

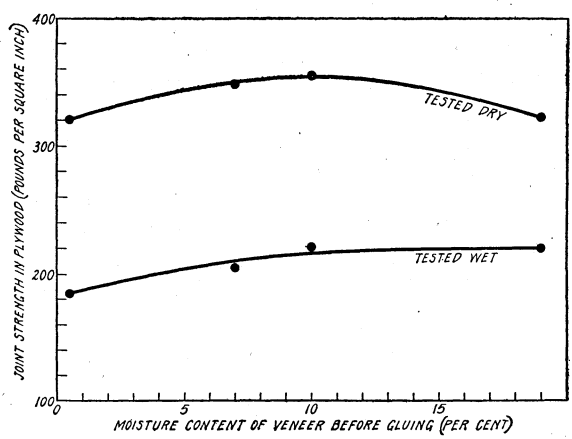


FIGURE 8.—Effect of moisture content of veneer upon the strength of plywood panels

depending upon the relative humidity of the surrounding atmosphere. In the manufacture of certain aircraft parts it may be necessary to control the relative humidity in the storage room or factory to obtain the best results. The relation of relative humidity to the moisture content of wood is shown in Figure 3.

LUMBER

CONDITIONING

Lumber that has been dried to the approximate average moisture content desired may still show differences between various boards and between the center and the outside of the same piece. A variation of 1 per cent in moisture content may be expected between boards of the same species even when they are of uniform dimensions and are exposed continuously under the same conditions of temperature and humidity. Larger differences may be adjusted by allowing the lumber to condition under suitable atmospheric temperature and humidity until the moisture content of each board comes to equilibrium with the moisture in the surrounding air.

(Fig. 3.) The thickness of boards, kind of wood, and moisture differences present all affect the time required for the lumber to come to equilibrium.

MACHINING

Machining lumber before it is to be glued should accomplish three important objects: (1) Elmination of defects, (2) reduction to the proper dimensions, and (3) preparation of the contact surfaces for the glue. The stock should be conditioned to the desired moisture content prior to the machining. It is best to machine the stock just before gluing, so that the surfaces will not become distorted from atmospheric moisture changes. The surfaces for gluing should be smooth and true. Plies for cross-banded or laminated construction (fig. 9, A to G) should be of uniform thickness. A small variation in thickness in each piece may cause a difference of serious proportions, as, for example, when a number of similar pieces are piled in the same order as they come from a planer. Planer marks, chipped or loosened grain, and other surface irregularities are objectionable.

SCRATCHED AND TOOTH-PLANED JOINTS

Scratching, tooth planing, or sanding the surfaces to be glued is still practiced by many operators, who either believe that roughening and tearing up the surface fibers gives the glue a better chance to adhere to the wood or that the irregularities are cut away and flatter pieces, more uniform in thickness, are obtained. Investigations into the penetration of glue into wood and tests of the strength of well-made joints show no benefit from such practices (*24*).

SHAPED JOINTS CONTRASTED WITH PLAIN JOINTS

The fact that the tongue-and-groove and other shaped joints present a larger gluing surface than the plain joints is often considered a theoretical advantage. In practice, however, this advantage is often lost entirely or in part. Shaped joints are more difficult to machine than plain straight edges so as to obtain a perfect fit of the parts. Lack of contact may make the effective holding area smaller in the shaped joint than on a flat surface, and this may actually reduce the strength. Furthermore, if proper conditions are maintained, plane tangential or radial surfaces (fig. 9, A to G) of most woods can be glued so as to develop the full strength of the wood, and the extra contact surface therefore becomes superfluous so far as strength is concerned.

In edge-joint gluing, however, the tongue and groove is an advantage in that the pieces are held in alignment during the assembling process and there is less slipping of the parts when pressure is applied. This makes possible more rapid clamping in many operations. When end-grain surfaces have to be joined, as illustrated in Figure 9, H and I, cutting to sharp angles and the use of reinforcing members are usually necessary.

VENEER

Veneer is cut by three different methods—sawing, slicing, and rotary cutting. By far the largest part of all veneer is cut by the rotary process because it is cheaper and involves less waste in manufacture. Both rotary-cut and sliced veneers are checked somewhat on the side of the sheet next to the bolt or flitch (pl. 9, B) during the manufacturing process whereas sawed veneer is more uniform

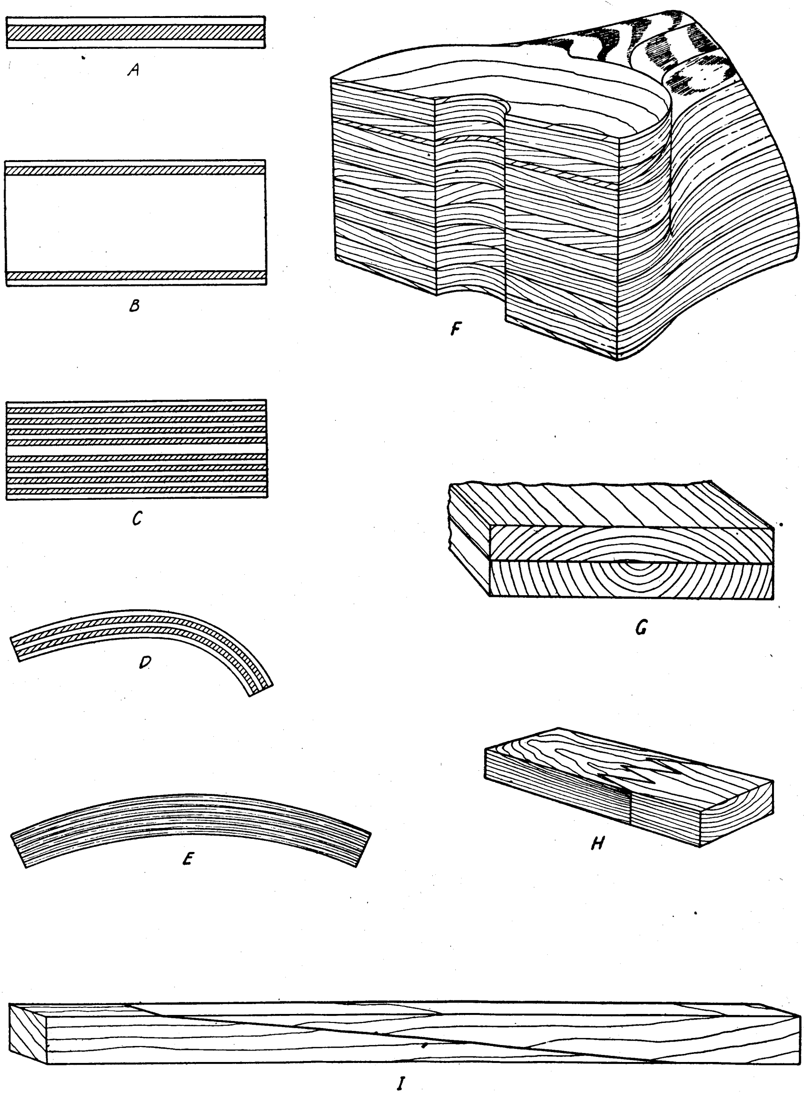


FIGURE 9.—Types of joints: A, Plywood (all veneer); B, plywood (lumber core); C, plywood (lumber or veneer core); D, bent plywood (all veneer); E, curved laminated construction; F, laminated propeller hub; G, section of laminated beam; H, serrate or finger joint; I, scarf joint

in properties on the two sides of the sheet. The amount of checking varies with (1) the kind of wood, (2) the thickness of the veneer cut, (3) the preparation of the bolt or flitch for cutting, and (4) the efficiency of the machine-cutting operation. Woods with small pores, such as birch, gum, and poplar, are easier to cut without serious checking than woods with large cells, such as oak and ash. Thick stock is more liable to check in cutting than are thin sheets. Proper heat treatment of the bolt and flitches is important for best results in both rotary cutting and slicing.

There appears to be no reason why plywood for aircraft should not be made from well-cut veneer made by any of the three methods. Comparative strength and warping tests, which were made on plywood manufactured from well-cut veneer by the three processes and from the same logs, showed no consistent differences in properties. On the other hand, badly checked veneer when used as cores in 3-ply panels (pl. 9, C) is known to reduce the joint strength in the plywood and should therefore be rejected for aircraft work.

The following characteristics are important in selecting veneer for use in aircraft: (1) Uniformity of thickness in the same piece; (2) smoothness and flatness; (3) freedom from large checks or other defects (pl. 9, B); and (4) straight grain and absence of decay (pl. 9, D).

GLUING TECHNIC AS RELATED TO THE QUALITY OF GLUE JOINTS

SATISFACTORY AND UNSATISFACTORY JOINTS

The conditions involved in the gluing operation must be controlled so as to produce a continuous film of solid glue in the joint with adequate adhesion to both pieces of wood. These conditions involve a sufficient spread of the glue on the wood surfaces and a correct balance between the consistency of the glue at the time of pressing and the amount of pressure used. A satisfactory joint and two common types of unsatisfactory joints, resulting from different gluing conditions, are shown in Plate 10. The three joints were all made from the same kind and quality of glue and wood, prepared in the same way. The "starved" joint (pl. 10, B) illustrates the result of one extreme, where the glue is too thin, and the "chilled" or "dried" joint (pl. 10, C) the opposite, where the glue is too thick, for the amounts of pressure used. A correct balance of the consistency of the glue and the amount of pressure used gave the good joint. (Pl. 10, A.) The starved and chilled joints are most commonly produced with animal glue, although the former may occur with any thin glue mixture. Dried joints may occur with all kinds of glues.

SPREADING THE GLUE

To make a satisfactory joint it is necessary to spread evenly the amount of glue needed, and for certain classes of work this should be done within as short a time as possible. These requirements can often be most easily met by machine spreading, but in the construction of aircraft from many small and irregular-shaped pieces, it is frequently necessary to spread by hand. Low-viscosity glues, such as warm animal glues, and most blood-albumin glues, spread easily by either method, but thick casein glues are difficult to spread by hand, and it is therefore best to use a machine spreader for them whenever possible.

SINGLE AND DOUBLE SPREADING

In most commercial gluing operations the glue is spread on but one of the two contact faces of the pieces being glued (single spreading). At times, however, both contact faces are coated if the greatest precaution is being taken to insure good joints. In order to determine the comparative value of the two methods a series of tests was made on plywood, a part of which was single spread with casein glue and the other double spread. The results of the tests, given in Table 4, indicate that the increase in strength by double spreading is slight.

TABLE 4.—*Comparison of results of tests on single and double spreading in gluing*

Method of spreading	Average[1] joint strength obtained when—	
	Tested dry	Tested wet
	Lbs. per sq. in.	*Lbs. per sq. in.*
Single	369	225
Double	377	235

[1] Each test value is an average of at least 75 specimens.

A more extensive test was made on thick laminations under a wider range of gluing conditions. The results again showed that good joints can be made by either method and that no great difference in strength of joints ordinarily occurs, whether one or both contact faces are coated, if other conditions are satisfactory. However, under adverse conditions of gluing, as when the glue became very thick before pressing, double spreading was found to be more reliable.

QUANTITY OF GLUE SPREAD

Within certain limits the strength of the glue joint increases with the quantity of glue spread. This is illustrated in Figure 10. The data are from plywood glued with casein glue under good gluing conditions. In other tests it was found that with less favorable gluing conditions the quantity of glue spread affected the joint strength to a still greater extent. The same general relationship holds for other glues, although the optimum amount of spread and rate of change in strength vary somewhat.

A spread of 1¼ ounces of wet glue per square foot of single glue line (about 38 square feet per pound of dry glue mixed 1 part glue to 2 parts water) is satisfactory for most conditions and kinds of gluing. A larger or smaller quantity may be used advantageously under certain conditions. With casein and blood-albumin glues a spread of more than 1¼ ounces apparently neither lowers nor increases the joint strength materially, whereas a smaller quantity normally produces inferior joints. Tests have shown that animal glue has a wider range of satisfactory spread for maximum joint strength, the amount to use being determined by the gluing conditions; good joints may be obtained with spreads of 1 to 1¾ ounces per square foot if other conditions are adjusted accordingly. A larger quantity of glue is required when both contact surfaces are coated and when conditions are such that the glue dries considerably on the wood before pressing. Warm wood, a long assembly time, and exposure to the air are factors that bring about quick drying of the glue.

CONSISTENCY OF GLUE MIXTURE

The consistency of the glue at the time of pressing is perhaps the most important factor in making satisfactory joints. However, the consistency of glue after being spread on the wood is extremely variable, depending upon such factors as the kind of glue, glue-water proportion of the mixture, quantity of glue spread, moisture content of the wood, temperature of the glue, room, and wood, the time elapsing between spreading and pressing, and the extent to which the glue-coated surfaces are exposed to the air. The kind of glue and the moisture content of the wood should be predetermined by conditions of service. The other factors may be varied somewhat to suit the particular gluing operation.

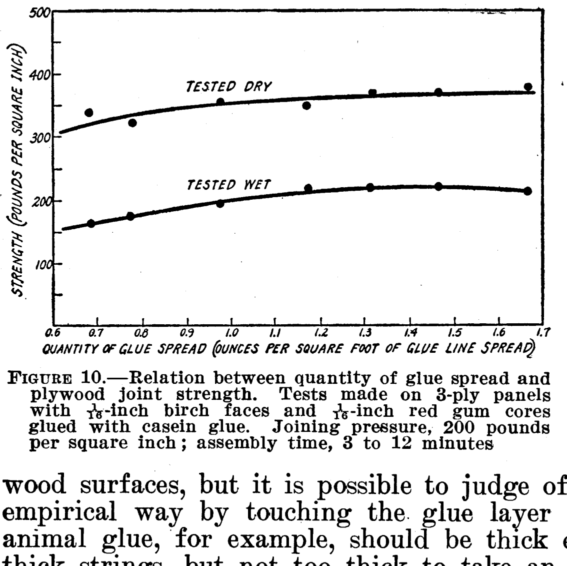
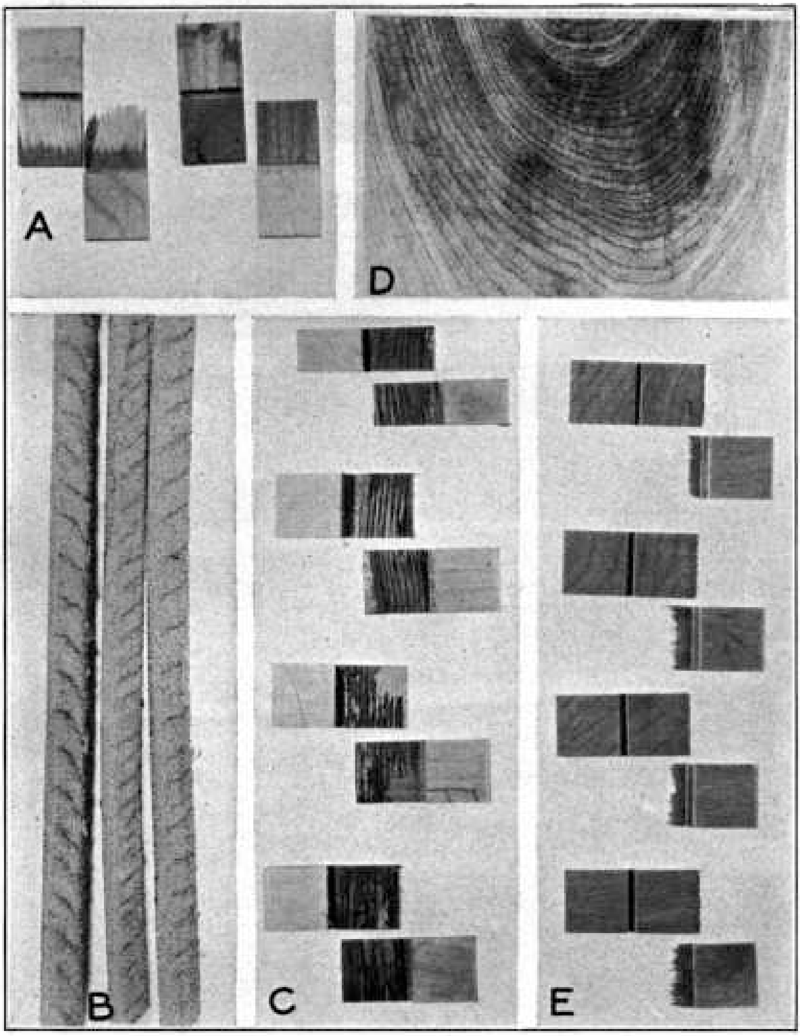


FIGURE 10.—Relation between quantity of glue spread and plywood joint strength. Tests made on 3-ply panels with $\frac{1}{16}$-inch birch faces and $\frac{1}{16}$-inch red gum cores glued with casein glue. Joining pressure, 200 pounds per square inch; assembly time, 3 to 12 minutes

It is very difficult to measure the viscosity of a glue mixture after it is spread on wood surfaces, but it is possible to judge of the consistency in an empirical way by touching the glue layer with the fingers. An animal glue, for example, should be thick enough to form short, thick strings, but not too thick to take an imprint or depression readily. Between the two conditions thus defined good results are produced with a moderate amount of pressure. At the time of pressing a glue of the proper consistency will flow sufficiently to show a distinct line of glue at the joint edge. (Pl. 10, A.) The absence of a line of glue at the joint indicates a chilled or dried joint. (Pl. 10, C.) If, on the other hand, the glue flows out and down over the edges of the pieces excessively it indicates the likelihood of a starved joint. (Pl. 10, B.)

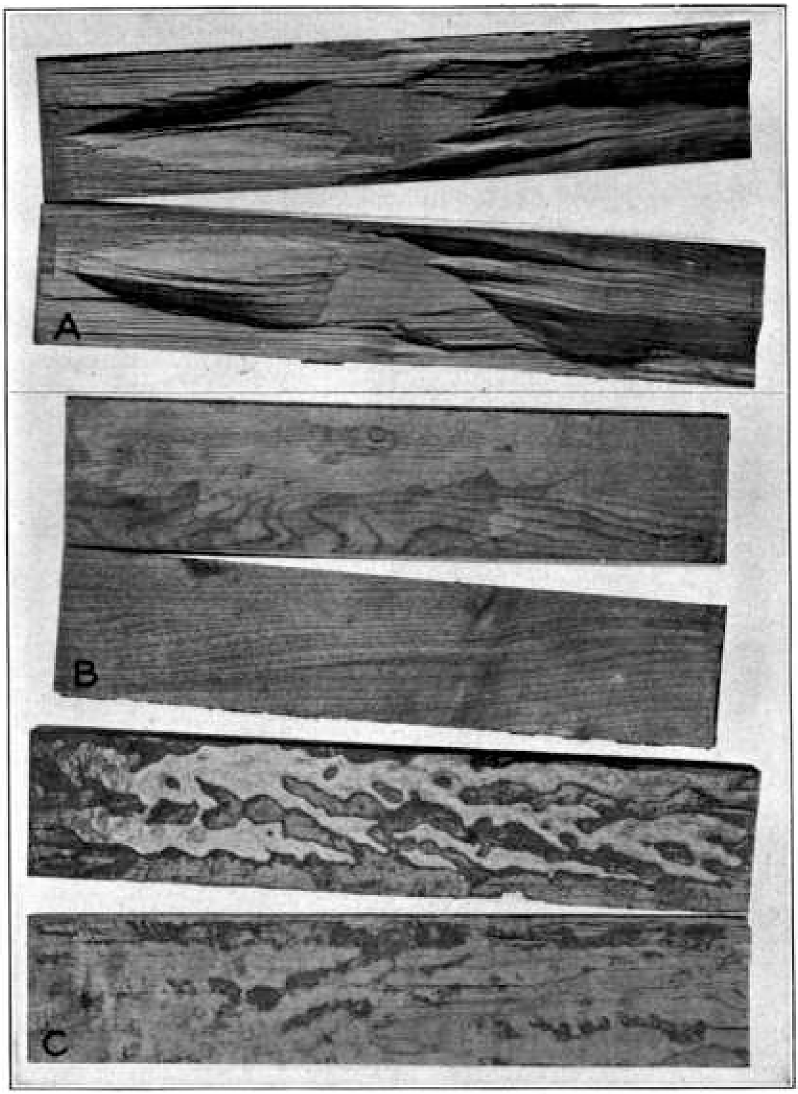
EFFECT OF ASSEMBLY TIME AND TEMPERATURE

Where pieces of wood are coated and exposed freely to the air a much more rapid change in consistency of the glue occurs than where the pieces are laid together as soon as the spreading (single or double) has been done. The condition of free exposure is conveniently referred to as "open assembly," and the other as "closed assembly."



QUALITY OF VENEER AFFECTS STRENGTH OF PLYWOOD

A, Strong joints glued from straight-grained well-cut veneer; B, veneer badly checked in cutting, not suitable for aircraft plywood; C, plywood test specimens, with core of checked veneer shown in B, failed by breaking from check to check and gave low strength values; D, cross-grained veneer, which should be rejected for aircraft use; E, broken plywood specimens with a cross-grained face ply similar to D. The cross-grained breaks resulted in low strength values.



STRONG AND WEAK JOINTS RESULTING FROM DIFFERENT GLUING CONDITIONS

A, Well-glued joint, made with a proper relation between pressure and consistency of glue; B, starved joint, resulted from the application of pressure while the glue was too thin. Occurs frequently with animal and other thin glue mixtures on certain woods; C, chilled joint, glue chilled excessively and amount of pressure was insufficient to bring about complete contact. Glue that dries excessively before pressing gives the same result.

The effect of the time element on the strength of casein-glue joints under closed-assembly conditions is illustrated in Figure 11. The results shown are for eight groups of plywood panels spread with glue in succession and pressed together in the same press, giving different assembly times. The assembly time was shortest for the last panels spread. The consistency of the glue at the shortest assembly periods was too thin and at the longest periods had become too thick to give the best joint strength at the pressure used. In other tests the use of somewhat lighter pressure at early periods and a heavier pressure at later periods was found to give more uniform joint strength, but such variation is, of course, impossible where all the panels are pressed at one time.

Of the glues used for woodworking, animal glue normally shows the largest change in consistency during the gluing operation. This is due primarily to the striking effect of cooling in increasing the viscosity of an animal-glue solution, illustrated in Figure 12. The change of viscosity of other glues from the effect of temperature is small in comparison, even if they are subjected to the same temperature changes, which is seldom. However, with all glues a rather indirect effect of temperature is the thickening of the glue solution by drying. High temperatures, especially of the wood, dry the glue on the wood surfaces more rapidly than do lower temperatures. For animal glue on wood at high temperatures (120° to 140° F.) this thickening from drying is the only means of bringing the glue to a proper consistency for pressing, and the process is slow. The cooling of the glue is rapid on wood at relatively low temperatures (70° F.) and becomes the controlling factor in producing a proper consistency, the drying effect becoming relatively unimportant. With animal glue, therefore, a definite control of temperature is necessary or, if changes in temperature occur, other conditions must be varied to prevent or compensate for differences in consistency (p. 27).

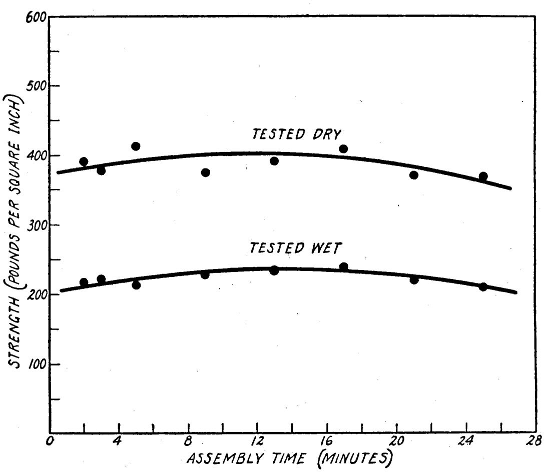


FIGURE 11.—Effect of assembly time on the joint strength of plywood glued with casein glue. Tests were made on 3-ply panels with $\frac{1}{16}$-inch birch faces and $\frac{1}{16}$-inch red gum cores. The joining pressure was 200 pounds per square inch

Satisfactory joints are obtained with both casein and blood-albumin glues when applied at room temperatures ranging from about 70° to 90° F., and variations within this range do not require any important change in other conditions, such as assembly time or amount of pressure.

The approximate ranges in time at which average mixtures of aircraft glues reach a satisfactory consistency for pressing under

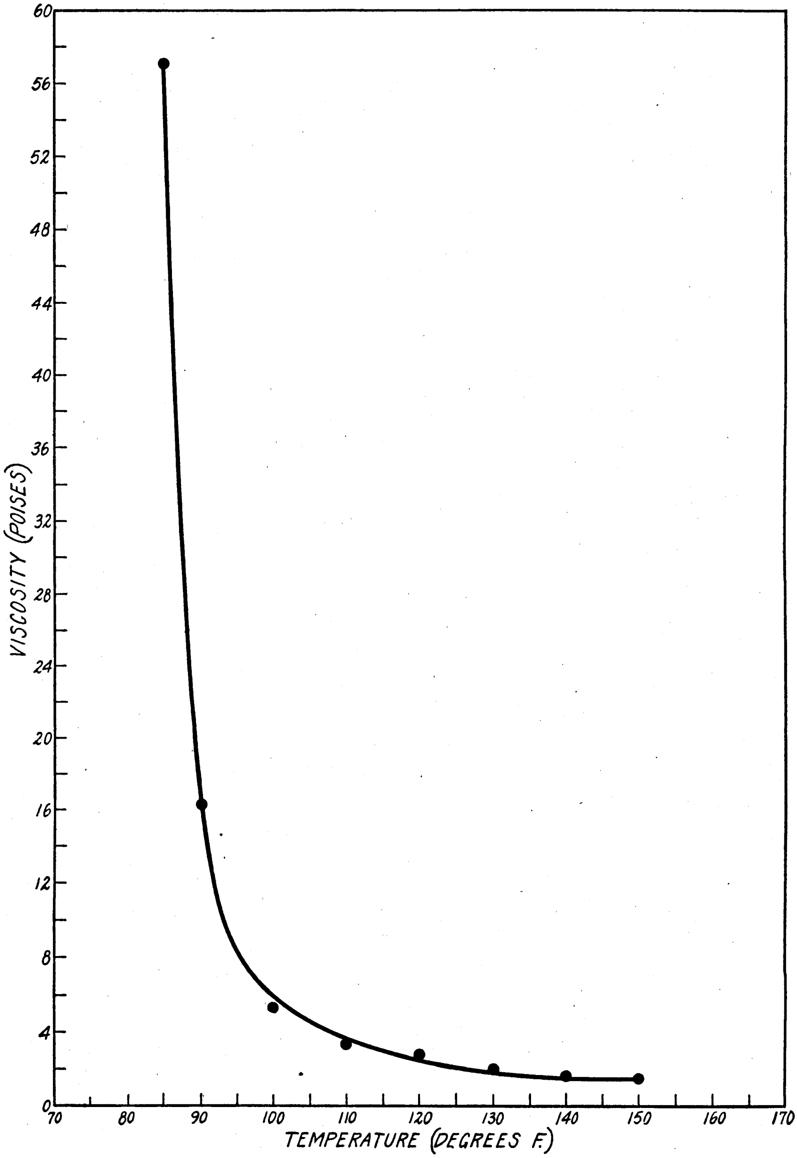


FIGURE 12.—Relation between temperature and viscosity of an animal glue that meets aircraft specifications. The tests were made on a solution mixed 1 part of dry glue to 2¼ parts of water

open and closed assembly and different temperatures are shown in Table 5.

TABLE 5.—*Range in assembly time for different glues*[1]

Kind of glue	Manner of assembly	Temperature of— Room	Temperature of— Wood	Approximate assembling time
		°*F.*	°*F.*	*Minutes*
Casein	Closed	70	70	0 -20
Do	Open	70	70	0 - 8
Blood-albumin	Closed	70	70	5 -20
Animal[2]	do	70	70	½- 1
Do	do	80	80	3 - 5
Do	do	90	90	10 -20
Do	Open	70	70	½- 1
Do	do	80	80	1 - 2½

[1] Conditions other than those given in the table were assumed as follows: Customary mixtures of the glues, spread 1¼ ounces per square foot and pressed with 200 pounds pressure per square inch of joint area.
[2] Animal glue of the minimum properties required in U. S. Army Specif. No. 3-140 (1927) and U. S. Navy Dept. Specif. No. 52G4C (1925).

The foregoing combinations of assemblies and temperatures are given as a guide and may be varied, provided other conditions are changed. For example, mixing a glue solution thicker than customary would lower the time limits between which the joints can safely be pressed. A pressure of more than 200 pounds per square inch would extend somewhat the maximum time limit, while a pressure less than 200 pounds per square inch would lower the minimum time limit. In general, longer assembly times are advisable with thin glue mixtures, heavy spreads, and high pressures, and shorter assembly times may be used successfully with thicker mixtures of glue and lighter spreads and pressures.

In gluing small parts at room temperatures it is ordinarily not difficult to apply the pressure when the glue has a proper consistency for moderate pressure. In larger operations, as in gluing propellers or plywood, the lapse of time varies considerably, and consequently the consistency of the glue spread first and that spread last in the same construction or stack of panels is not the same. In such cases a set of conditions must be selected that gives a sufficient time range (p. 41).

Temperature, aside from its effect upon consistency and the resulting strength of the joint, also influences the rate at which the glue sets and at which the joint gains strength under pressure (p. 32).

PRESSING AND CLAMPING

Pressure on the joint during the early setting of the glue is required for best results in practically all types and forms of gluing. The functions of pressure are to spread the glue out into a continuous film between the wood layers, to force air from the joint, to bring the wood surfaces into intimate contact with the glue, and to hold them in this position during the setting of the glue.

METHODS OF APPLYING PRESSURE

The methods employed in applying pressure to glue joints in aircraft manufacture range from the insertion of brads and screws to the use of powerful hydraulic and electric power presses. Figure 13 illustrates some of the means used for applying pressure by hand.

In a large number of joints in the wing structure the insertion of brads and small nails is the method commonly used. (Fig. 13, A.) The spring clamp (fig. 13, B) is used some in gluing small, narrow

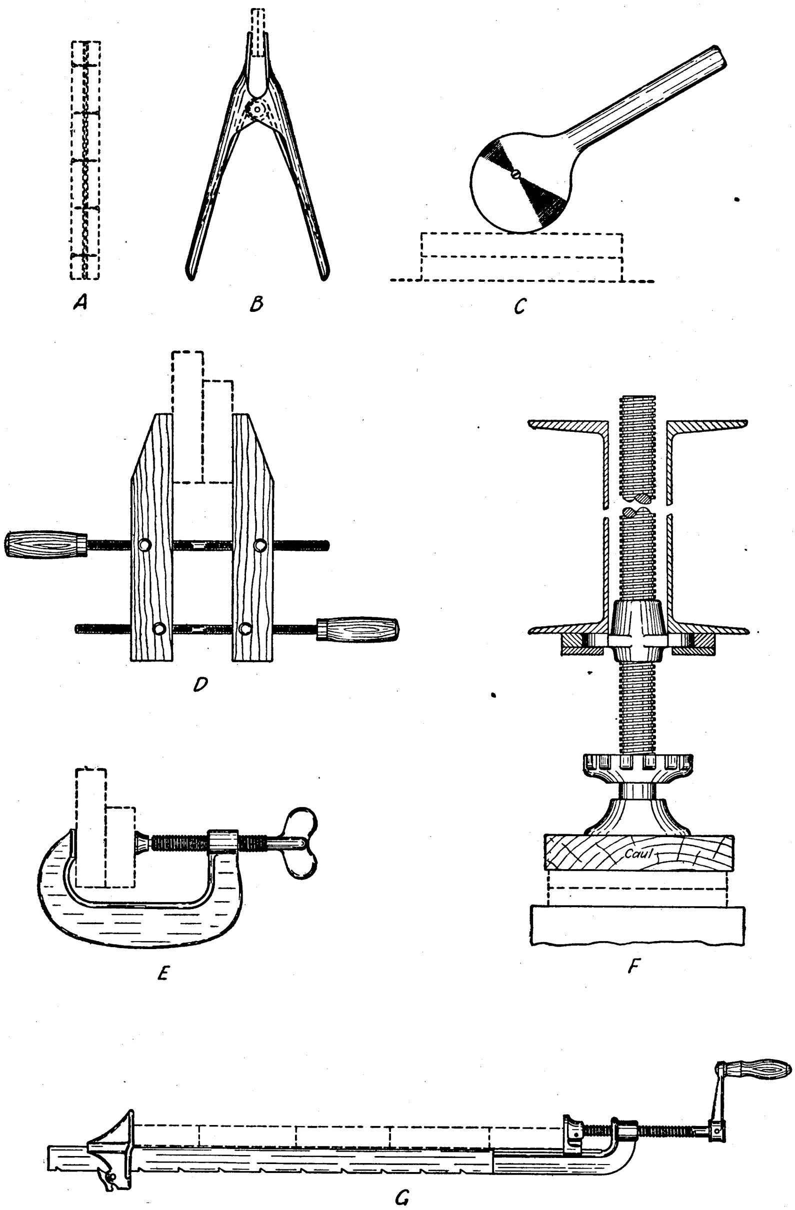


FIGURE 13.—Hand devices used in applying pressure to glue joints: A, Brads or nails; B, spring clamp; C, eccentric clamp; D, wood clamp; E, C clamp; F, jack-screw; G, bar clamp

joints, and the eccentric clamp (fig. 13, C) in applying pressure to the flanges of box beams when gluing the reinforcing blocks in place.

Wood clamps and C clamps (fig. 13, D and E) are extensively used in gluing spars, spar flanges, reinforcing blocks, and bow ends. (Pls. 11 and 12.) The larger laminated members, such as spars and propellers, are usually pressed under jackscrews (fig. 13, F) mounted on frames (pl. 12, A) where several are used on the same joints. The bar clamp (fig. 13, G) is useful when gluing pieces edge to edge.

The amount of pressure that can be applied with different types of equipment varies enormously. The amount of pressure applied by a single brad may be only a matter of pounds whereas several tons may be applied with the jackscrews. Tests made on some devices of the types illustrated in Figure 13 have provided the data shown in Table 6, which may serve as a guide in the use of similar pressure equipment. Where the screws of clamps and presses differ from those illustrated in Figure 13 and Table 6 the approximate loads may be calculated from the formula given in footnote 2 of Table 6. In gluing plywood, power presses, either of the hydraulic or electric types (pl. 13), are commonly used in which loads up to several hundred thousand pounds can be applied. Such presses are usually equipped with pressure gauges.

TABLE 6.—*Pressure data on screw clamps and other devices used in gluing*

Equipment tested	Force applied	Length of lever arm	Pitch of screw	Diameter of screw	Total load [1]	Coefficient of friction
	Pounds	*Inches*		*Inches*	*Pounds*	
Jackscrew	[1] 170.0	37	1/3	1 5/16	33,850	[2] 0.1978
Do	[1] 170.0	18	1/3	1 5/16	16,350	[2] .1997
Do	[1] 170.0	31	1/2	2 5/16	16,720	[2] .2000
Do	[1] 140.0	7	1/8	7/8	7,500	[2] .2498
C clamp	[2] 70.0	1 3/4	1/8	9/16	1,585	[3] .20
Do	[2] 69.5	3	1/8	9/16	2,700	[3] .20
Do	[2] 70.2	2	1/5	1 1/16	1,370	[3] .20
Bar clamp	[2] 79.9	2 1/2	1/8	1/2	2,810	[3] .20
Wood clamp [4]	[2] 71.3	1/2	1/14	3/8	720	[3] .20

[1] Measured in test.

[2] Calculated from the formula $FL=WRm\left(\frac{f\,Dm+K}{Dm-fK}\right)$, which is applicable to square-thread screws.

Where F=force applied to lever arm in pounds.
L=length of lever arm in inches.
W=load in pounds.
Rm=mean radius of screw in inches.
f=coefficient of friction.
π=3.1416.
Dm=mean diameter of screw in inches.
K=pitch of screw (single thread) or lead (multiple thread).

[3] Assumed from results of previous tests.

[4] Screws with V-type threads; hence calculation from formula is only approximate.

To secure the best results in gluing, the pressure should be distributed uniformly over the joint area. High pressure at certain points and low pressure at others results in weak spots or areas in the joint. Blocks and cauls are frequently used between the clamp or press and the layers being glued to distribute the load from the point of contact to other parts not directly under the load. This is particularly necessary where thin plies are glued. Obviously such members must be true and uniform in dimension or they do not fulfill their purpose. Other principal causes of unequal pressure on joints are: (1) Irregular surfaces of the wood pieces being glued; (2) unequal thicknesses or width of stock; (3) improper spacing of the pressure-bearing members; and (4) deflection and other imperfections in press, clamps, or other pressing equipment.

Where heavy loads are applied, as in gluing propellers and plywood, large deflections of the press members may, and frequently do, occur. This is most often true with heavy screws of the type shown as Figure 13, F, and where I beams and retaining clamps are used with bundles of veneered panels for retention of pressure after removal from the press. (Pl. 13, A.) The presses should be designed rigid enough and the retaining I beams should be stiff enough and spaced sufficiently close so that undue deflection will not occur. Likewise, the platens and other large bearing surfaces of large presses should be smooth, true, and parallel.

The load originally applied to glue joints tends to drop as the glue squeezes out from between the wood layers and distributes itself in the joint. Care should be used that the correct amount of pres-

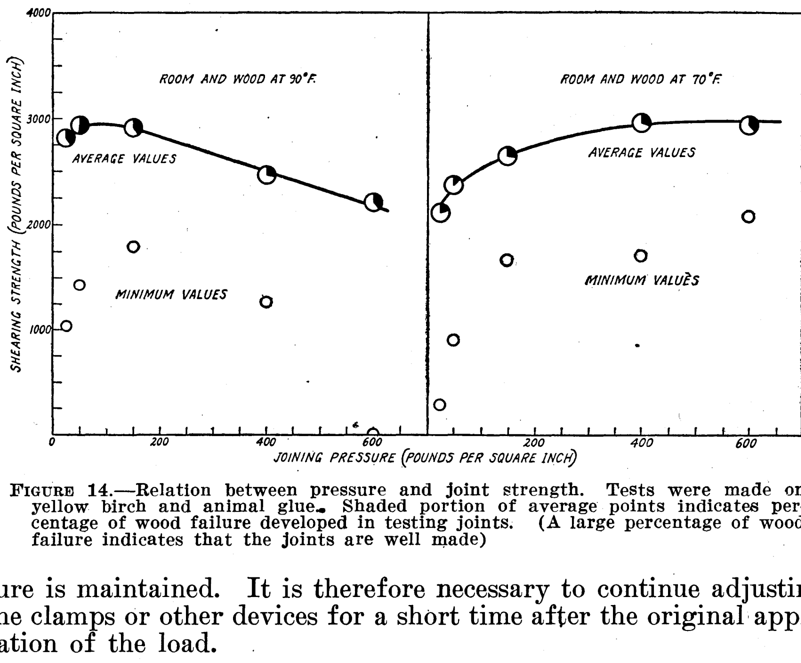


FIGURE 14.—Relation between pressure and joint strength. Tests were made on yellow birch and animal glue. Shaded portion of average points indicates percentage of wood failure developed in testing joints. (A large percentage of wood failure indicates that the joints are well made)

sure is maintained. It is therefore necessary to continue adjusting the clamps or other devices for a short time after the original application of the load.

AMOUNT OF PRESSURE

A light pressure should be used with a thin glue, a heavy pressure with a thick glue, and corresponding variations in pressure should be made with glues of intermediate consistencies. In Figure 14 are shown the results of joint tests made on 1-inch stock with animal glue, which illustrates the relation between the amount of pressure and the resulting average joint strength. From these and other data the curve of Figure 15 was derived, showing pressures recommended by the Forest Products Laboratory for different consistencies of glue.

While it is possible to make strong joints with pressures of less than 50 pounds per square inch, such pressures are generally not feasible under commercial conditions. The successful use of light pressures presupposes that the wood surfaces are free from warping and other irregularities—a condition that seldom prevails. Pres-

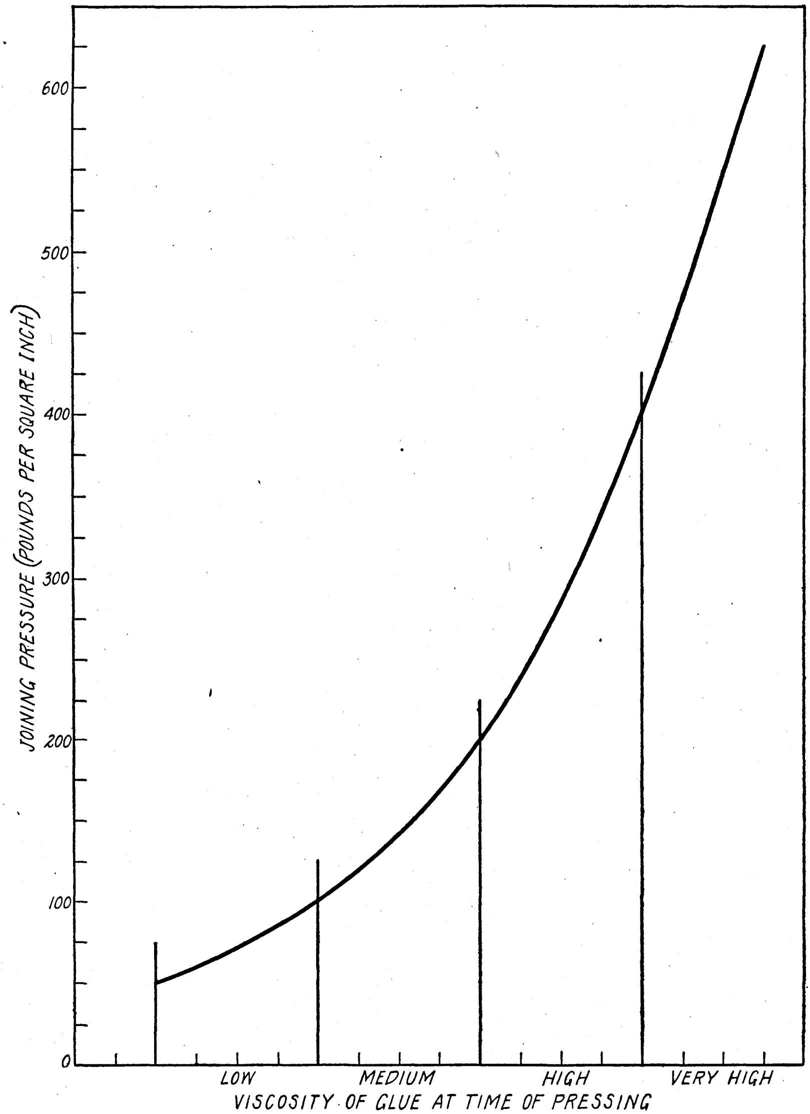


FIGURE 15.—Joining pressures recommended for glues of varying consistencies. Low viscosity, represented by thinly mixed, warm animal glues and thinly mixed blood-albumin glues; medium viscosity, represented by thickly mixed blood-albumin glues, slightly cooled animal glues, and thin casein glues; high viscosity, represented by thick casein glues, semijellied animal glues, and blood-albumin glues; very high viscosity, represented by firmly jellied animal glues

sures in excess of 200 pounds per square inch may crush certain woods, and pressures as high as 400 pounds per square inch are applicable only to the strongest species of wood. In general, experimental and practical work has justified the use of a pressure of about 200 pounds per square inch and a medium-high viscosity of glue where maximum strength of joint is required.

The occurrence of an occasional weak joint or part of a joint, which may cause failure in service, is of great significance to the builder of aircraft. The selection and control of gluing conditions so as to avoid weak spots in the joints is of even greater importance than the average strength of the joints. Figure 14 shows the effect of the amount of pressure on minimum values in joint tests made with animal glue.

Figure 16 shows the gluing conditions under which low strength joints are most likely to occur when gluing with casein glue.[16]

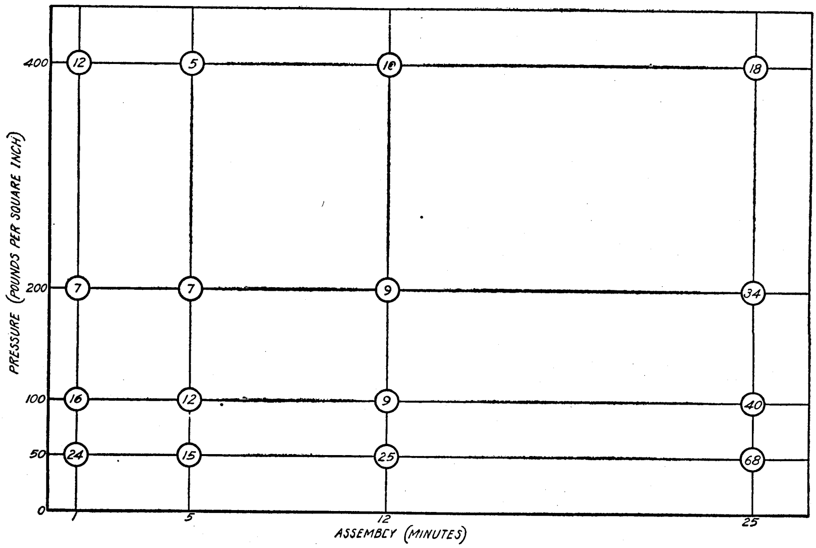


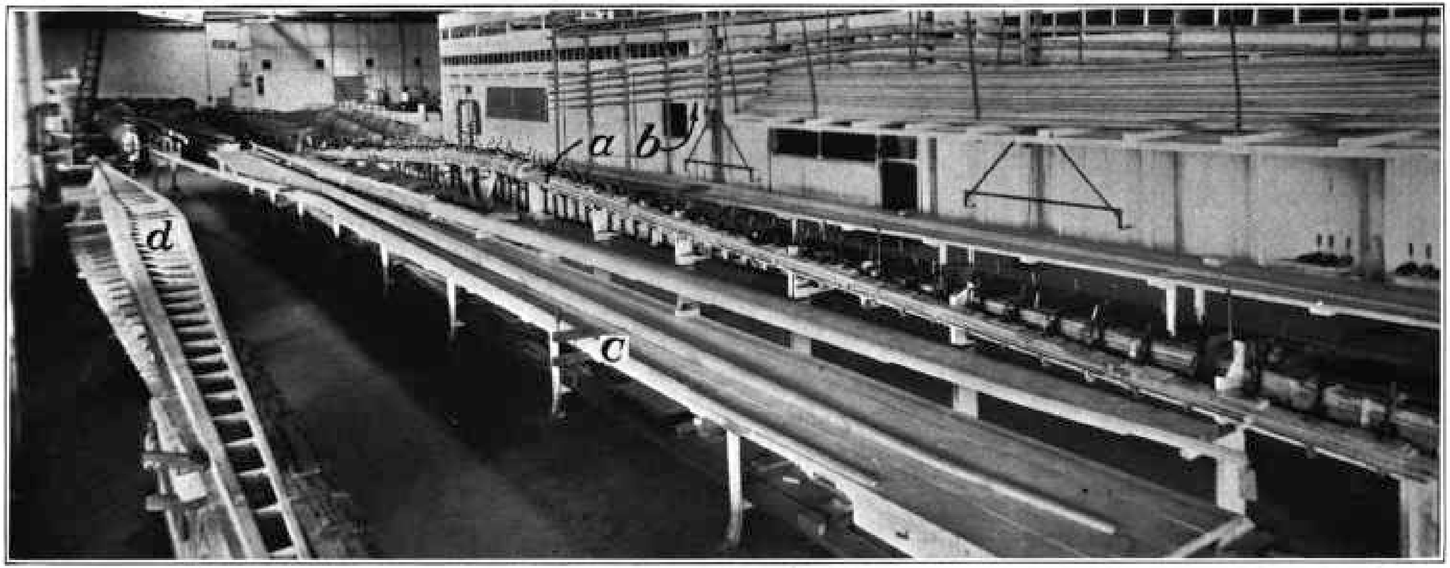
FIGURE 16.—Occurrence of low joint strength in relation to gluing conditions with casein glue. Figures in circles represent the number of low-strength joints occurring with each combination and pressure and assembly time.

Twenty-four species of wood were glued in these experiments, under 16 combinations of gluing conditions. Ten test specimens were made from each species under each gluing condition which made a total of 160 specimens for each species and 3,840 for the 24 different woods. The lowest 10 per cent of the strength values of each species were separated and arranged under the conditions producing them, excluding, however, the values where failure was completely in the wood. The largest number of weak joints occurred with long assemblies and low pressures, and the smallest number with the short assemblies and high pressures.

DURATION OF PRESSURE

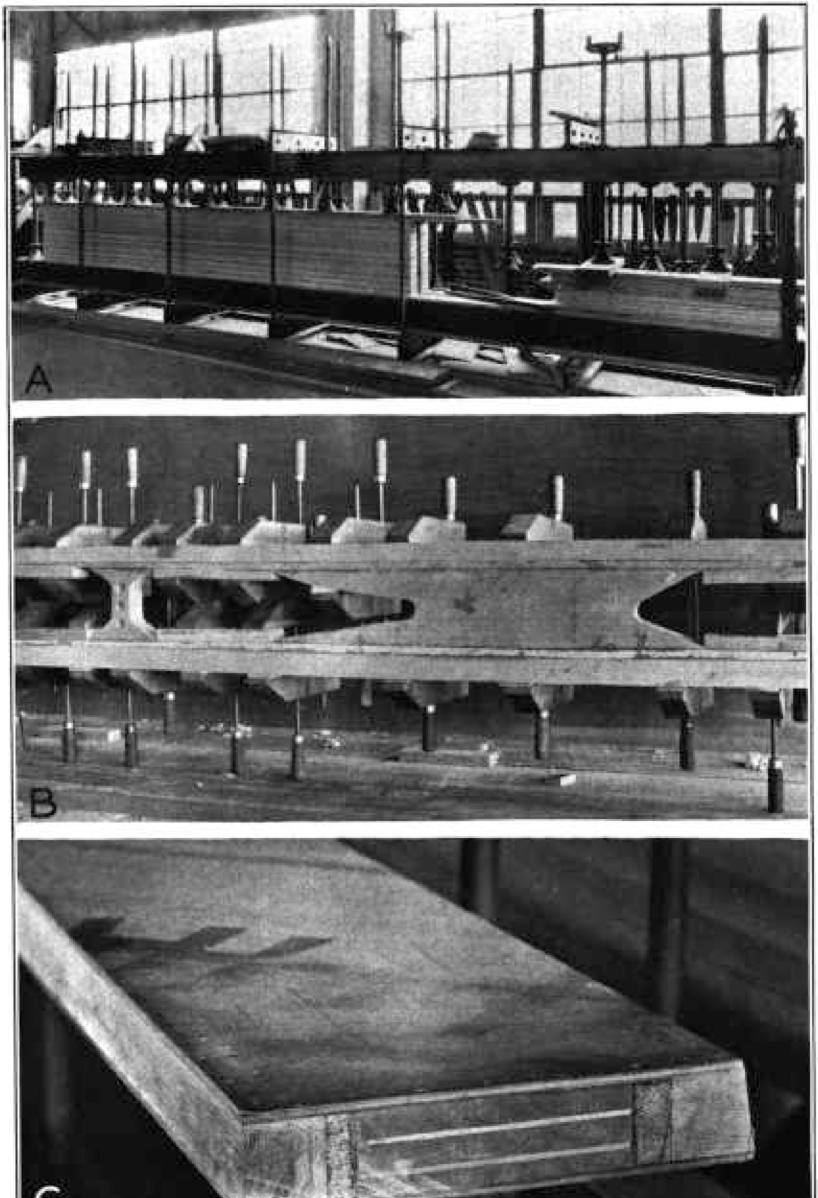
Joints should be retained under pressure at least until they have a sufficient strength to withstand the internal stresses tending to sepa-

[16] The glue mixture contained about 10 per cent less water than shown in formula No. 4B (p. 54) and was slightly thicker than an average casein glue.



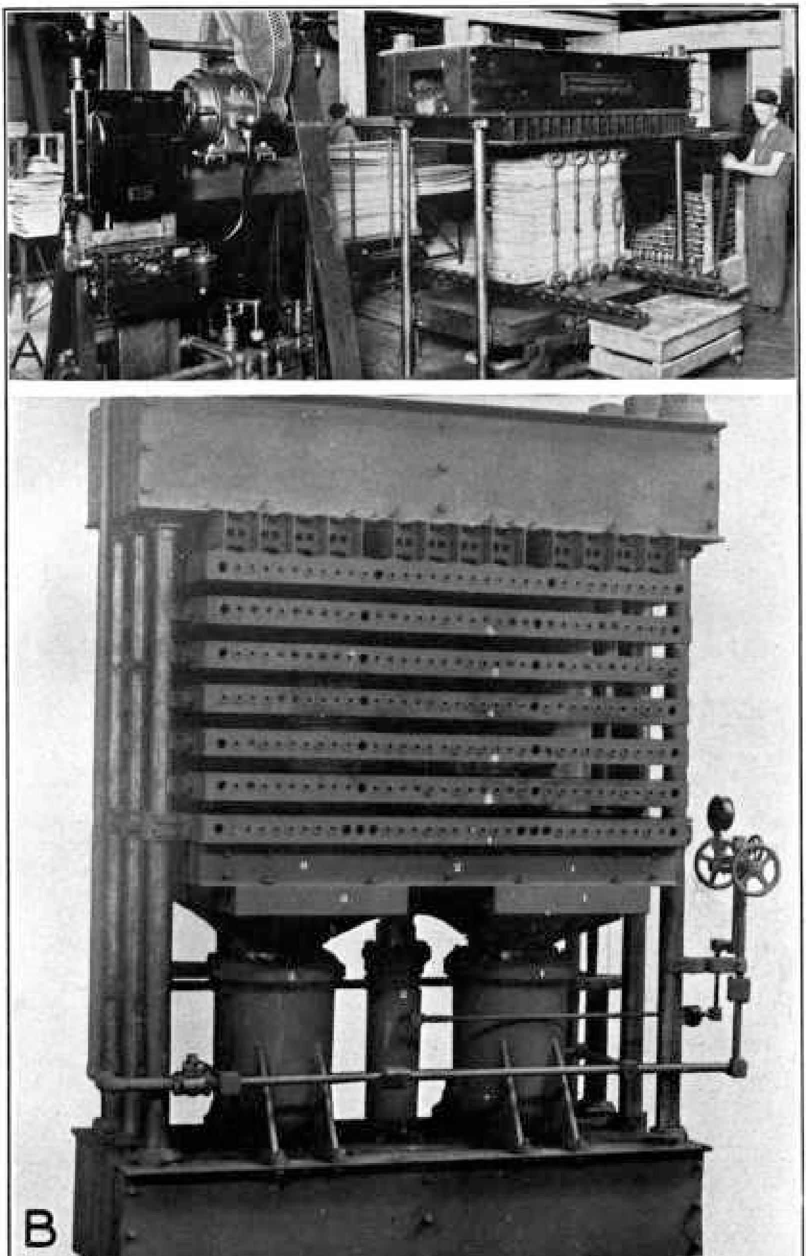
A BOX SPAR GLUING OPERATION

A, Laminated flanges being glued; *B*, conditioned; *C*, worked to size, and *D*, assembled preparatory to gluing on the plywood sides. Pressure is applied to the spar flanges in gluing by means of C clamps.



SPAR CONSTRUCTION

A, An aircraft factory press loaded with laminated spars of solid construction. Two pieces of spruce are glued together to form one spar. Pressure per square inch of joint area is from 125 to 150 pounds; B, gluing reinforcing blocks to the flanges of a box spar. Pressure, applied by means of wood clamps, is insufficient and not properly distributed for making the best joints: C, a box spar showing laminated flanges, 5-ply reinforcing block, and 3-ply veneer sides. The plywood sides were pressed to the framework of the spar by the use of brads only.



POWER PRESSES USED IN GLUING PLYWOOD

A, Hydraulic, cold press showing stack of panels with I beams and retaining clamps in place; B, hydraulic, hot plate press used in the manufacture of blood-albumin glued plywood.

rate the wood pieces. It is safe to assume that under favorable gluing conditions this stage will be reached in from two to seven hours, according to the thickness and absorptive power of the wood. A pressing period beyond the minimum is advisable as a precautionary measure where operating conditions permit.

The rate at which the joints gain strength is the principal factor determining the length of time in the press. Joints increase in strength mainly as a result of drying of the glue layer, and drying is in turn affected by several factors. The quickest release of pressure is possible when a fast-setting glue, a thin spread, and warm, dry, thick layers of wood are used in a warm room.

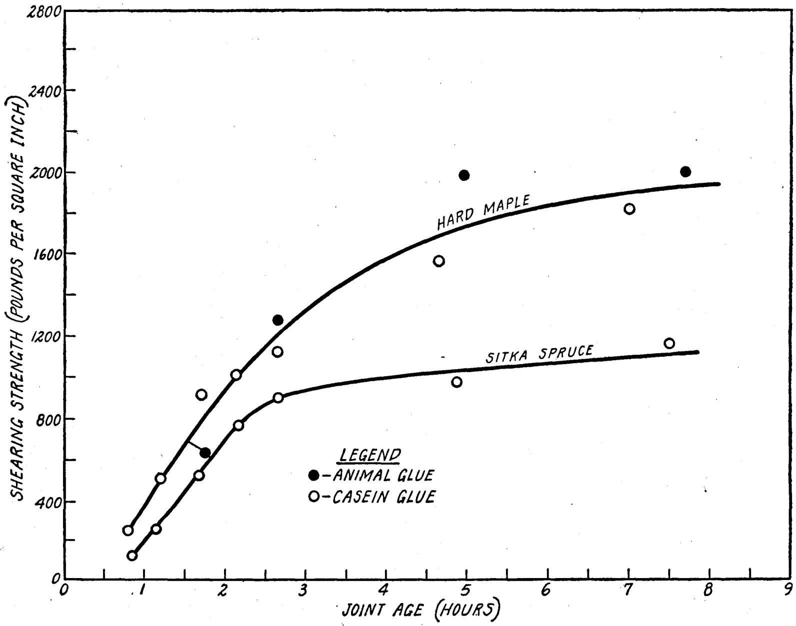


FIGURE 17.—Strength-time relation for animal and casein glue joints. Tests were made on ¾-inch hard maple and Sitka spruce as soon as possible after joints were taken from press. Each value is an average of at least 24 test specimens from 6 or more joints

Figure 17, showing the increase of strength of joints with time of pressing, is based on tests of animal and casein glues. The gluing was done under conditions favorable to the production of strong joints. The rates of increase in strength of the two glues are approximately equal when the glues are used in a room and on wood at a temperature of about 70° F. Animal-glue joints made in a warmer room and on heated wood showed a more rapid increase in strength, and in all probability the same would be true for casein glue. The higher temperatures apparently increase the drying rate, but they are also known to be a serious cause of lower final strength of joints. In the tests represented in Figure 17 the glue was as strong in shear after 6 hours of pressing as the maple wood adjacent the glue line. In the tests with spruce, the glue was as strong as the wood in 4 hours. The strength shown for sugar-maple joints at the end of about 8 hours of pressing by no means represents the final strength of the joints. A further conditioning, extending in all over a 7-day period, permitted an equalization of moisture which resulted in an average joint strength on sugar maple of approximately 3,000 pounds per square inch. In other tests of the same series, joints, which were pressed for 2 hours and then allowed to season for 22 hours, proved as strong as those that had been pressed for 24 hours. Sugar-maple joints pressed for only one-half hour and seasoned for 24 hours, although of fair average strength, showed greater variation and would not be so dependable where uniform maximum strength is important.

In gluing veneer the early setting of the glue is about as quick as in gluing thick joints, but beyond this the veneer joint appears to increase in strength more slowly. The thin layers of wood do not continue to absorb the moisture as rapidly from the glue as the thicker stock, and a longer pressing period is therefore required. Plywood is usually left under pressure for 18 to 24 hours, but this is determined more by routine of operation than by the rate of setting of the glue. Pressing plywood beyond 5 to 7 hours appears to be unnecessary if it has been properly glued, although the customary longer periods are not harmful and insure an additional margin of safety.

USE OF HEAT IN PRESSING

With most blood-albumin glues hot-plate presses are required in making joints. (Pl. 13, B.) The glue must be brought to a minimum temperature of about 160° F. to render the joint water-resistant. Heat and pressure are applied at the same time by means of steam-heated platens. The temperature of the platens usually ranges between 212° and 300°. With certain formulas temperatures of about 300° give the strongest and most highly water-resistant joints, but at the same time they are liable to develop blisters or steam pockets in the panels during the pressing process. The time required in pressing varies with the temperature of the platens and thickness and kind of the material being pressed. The variation in time in actual practice is from 2 or 3 minutes to as much as 30 minutes.

Casein glues for use in aircraft are usually pressed cold. Experiments have shown, however, that the quality and water resistance of casein-glue plywood can be substantially improved by the application of heat. Hot pressing after the joints had set but before they had dried resulted in a somewhat greater improvement than hot pressing at the time of gluing. With some brands of casein glues the wet strength of the resulting joint was increased by 35 to 40 per cent.

GLUING DIFFERENT SPECIES AND SURFACES OF WOOD

SPECIES GLUED

A very large part of the wood used in aircraft is Sitka spruce which, fortunately, is comparatively easy to glue. Ash, basswood, black walnut, mahogany, hard maple, white oak, and yellow poplar are also used and glued to some extent. Spruce does not require so careful control of gluing conditions as the other species in order to make joints of maximum strength. Ash, black walnut, birch, hard maple, and white oak will require very careful control of the gluing operation to obtain the best results.

Gluing tests have been made at the Forest Products Laboratory on about 40 different species, including those used most in aircraft construction. The woods were glued with animal, casein, and vegetable glues under a wide range of pressures and assembly times[17] and the joints were tested in shear in the manner illustrated in Figure 5. The joints which showed no marked or general variation in strength were taken as a basis for comparing the gluing characteristics of the different species of wood. From these tests definite recommendations have been made for the gluing of each species.[18] The results obtained with animal and casein glues are applicable to aircraft gluing.

In Figure 18 the average joint strengths of 31 species, which have been glued in aircraft or which from their properties and abundance may warrant consideration for aircraft purposes, are plotted against the specific gavity of the wood tested. The strength of wood is known to vary in a general way with its density, and from Figure 18 the same relation is seen to exist for glued joints, even where complete wood failure did not occur in testing.[19] The amount of wood failure occurring during test over the glue-line area was generally in reverse order to the strength of the points and the specific gravity of the woods. For example, Sitka spruce joints showed practically 100 per cent average wood failure (0 per cent of glue-line failure), mahogany about 80 per cent, and ash and birch each about 50 per cent.

RECOMMENDATIONS FOR GLUING SIDE-GRAIN SURFACES OF VARIOUS SPECIES WITH CASEIN GLUE

For gluing side-grain surfaces with casein glue the various species listed in Figure 18 are divided into two groups according to the conditions applicable, as follows:

Species	*Gluing conditions recommended*
GROUP 1	
Cedar, western red Fir, white Hemlock, western Pine, northern white Pine, western yellow Redwood Spruce, Sitka	Glue of medium consistency, spread 1¼ to 1½ ounces per square foot, pressure from 100 to 150 pounds per square inch, and assembly time 0 to 20 minutes closed, or 0 to 8 minutes open.

[17] Pressures of 100 to 400 pounds per square inch and assembly times of 1 to 25 minutes were used. Since 400 pounds pressure would have crushed some of the weaker woods, the highest pressure used was the maximum that the wood would stand without injury.

[18] For a more complete discussion of results and recommendations for the gluing of the 40 species see The Gluing of Wood (*24*).

[19] In the type of specimen used in testing the glued joints (fig. 5) the unit stress in the glue is higher than in the wood because the shearing load is borne by a larger area of wood than of glue line. Furthermore, the stress may be very close to the ultimate strength of the wood, and yet failure may occur chiefly or entirely in the glue line. For these reasons a high percentage of glue failure (low percentage wood failure) may occur in test and still the strength of the joint be as high as that of the wood itself.

Species	*Gluing conditions recommended*
GROUP 2	
Ash, white	Glue of thick consistency, spread 1¼ to 1½ ounces per square foot, pressure 150 to 200 pounds per square inch, and assembly time 0 to 12 minutes closed, or 0 to 6 minutes open.
Basswood	
Beech	
Birch, yellow	
Cedar, Alaska	
Cherry, black	
Cottonwood	
Elm, American	
Elm, rock	
Douglas fir	
Gum, black	
Gum, red (heart)	
Gum, red (sap)	
Gum, tupelo	
Hickory	
Mahogany	
Magnolia	
Maple, soft	
Maple, hard	
Oak, red	
Oak, white	
Poplar, yellow	
Sycamore	
Walnut, black	

Occasional weak joints in red gum (heartwood), black cherry, and hickory are obtained even when glued under the conditions recommended. This trouble can be largely avoided by treating the wood before gluing in the manner described on page 38. Sitka spruce, which is used extensively in aircraft, is very satisfactorily glued under the conditions recommended for Group 2 woods as well as those for Group 1, in which it is listed. On the other hand, white ash, birch, or hard maple is less satisfactorily glued under some of the conditions recommended for Group 1 woods and should, therefore, be glued under the more restricted conditions of Group 2.

WITH ANIMAL GLUE

The principal species of woods glued with animal glue in aircraft construction may be placed in a single group in so far as recommendations for gluing practices are concerned. The following species include the woods used for propellers and a few others requiring similar gluing technic: Ash, yellow birch, black cherry, red gum, magnolia, mahogany,[20] soft maple, hard maple, red oak, white oak, and black walnut. Gluing conditions recommended for these species of wood are shown in Table 7.

[20] The gluing conditions required for mahogany are less rigid than for the other species listed, but it glues satisfactorily under the conditions recommended.

TABLE 7.—*Gluing conditions recommended with animal glue for woods used in aircraft*

Glue-water[1] proportions, by weight	Approximate glue spread	Temperature of the wood	Pressure	Closed assembly[2] time
	Ozs. per sq. ft.[3]	°*F.*	*Lbs. per sq. in.*	*Minutes*
1 to 2¼	1¼–1½	70	150–200	½– 1
Do	1¼–1½	80	150–200	3 – 5
Do	1¼–1½	85	150–200	8 –15
Do	1¼–1½	90	150–200	10 –18

[1] A glue which meets the requirements of U. S. Army Specification No. 3-140, and Navy Department Specification No. 52G4C.
[2] Wood pieces are laid together as soon as spread with glue.
[3] Weight of wet glue mixture applied per square foot of glue line.

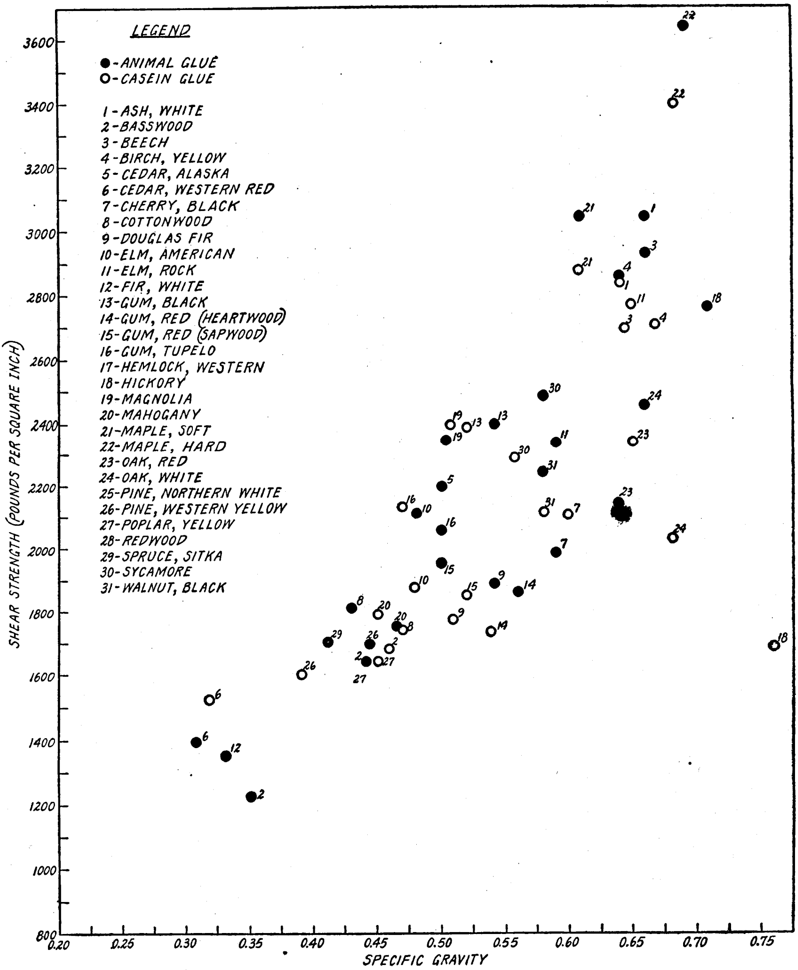


FIGURE 18.—Relation between specific gravity of wood and shear strength of joints of various species glued with animal and casein glues

Satisfactory gluing may be performed at other temperatures than those indicated in Table 7, provided an adjustment is made in the assembly time or other conditions. Heating the wood above 90° F. is ordinarily not advisable. Where it is impossible to apply the full amount of pressure recommended, the assembly time should be shortened or the temperature somewhat increased.

Because of the variability of results with red gum (heartwood) and black cherry, these species should not be used where maximum strength of joint is of primary importance unless treated in the manner described in Table 8.

TREATING THE WOOD BEFORE GLUING

With woods that are naturally difficult to glue or where conditions are not the most favorable to the production of strong joints it is possible to bring about stronger joints by treating the wood before gluing.

With animal glue, caustic soda proved to be one of the most effiective of several treating materials tried out experimentally. The wood surfaces to be joined were brushed with a 10 per cent solution of caustic soda, wiped after a few minutes to remove any dissolved material or excess of the solvent, allowed to dry, and then glued under standard gluing practice. The data in Table 8, derived from joint tests of yellow birch (heartwood) glued with animal glue, indicate the improvement resulting from the caustic-soda treatment.

TABLE 8.—*Results of caustic soda treatment on joints of yellow birch (heartwood) and animal glue*[1]

Condition of specimen	Shear strength of joint	Wood failure	Specific gravity of wood[2]
	Lbs. per sq. in.	*Per cent*	
Wood untreated (good joint conditions)	2,700	69	0.66
Wood untreated (starved joint conditions)	1,910	6	.66
Wood treated with 10 per cent caustic-soda solution (starved joint conditions)	2,770	88	.62

[1] Each test value shown represents at least 10 specimens.
[2] Specific gravity based on oven-dry weight and volume at 7 per cent moisture content.

Other species, which showed an improvement in joint strength when treated before gluing with animal glue were: Black cherry, red gum (heartwood), red gum (sapwood), hard maple, red oak, and white oak.

With casein glue, hydrated lime (10 grams added to 90 grams of water) gave slightly better results than caustic soda when used as a surface treatment for black cherry, hickory, and red gum. Hickory, which is difficult to glue with casein glue, produced appreciably better joints after treatment with either lime water or caustic soda.

GLUING END-GRAIN SURFACES

The methods, practices, results of tests on joints, and recommendations which have thus far been presented relate more specifically to the gluing of side-grain surfaces of wood. Such surfaces are involved exclusively in plywood and laminated constructions. (Fig. 9, A to G.) Joints between side-grain surfaces in most species can be made as strong in shear parallel to the grain, tension across the grain, or cleavage as the wood itself. The highest stresses developed in these joints do not exceed 3,000 or at the most 4,000 pounds per square inch.

The gluing of end-grain surfaces, on the other hand, is not accomplished with the same degree of success. Straight end-grain butt joints are rarely attempted in any type of construction, and where wood is subjected to tension stresses parallel to the grain, joints of this type can not be depended upon to develop more than a small part of the strength of the wood.

Most North American species of wood are capable of withstanding 6,000 to 20,000 pounds per square inch in tension parallel to the grain. Tests made in gluing straight end-grain surfaces have shown that such joints are erratic and rarely exceed about 3,000 or 4,000 pounds per square inch in strength. Their strength is limited by several factors including: (1) Structure of the wood, (2) penetration of the glue, (3) air bubbles in openings of the wood, (4) quality of glue, (5) consistency of glue, (6) application of glue, (7) amount and duration of pressure, and (8) shrinkage of glue.

Since factors 1, 3, and 8 are largely beyond operative control, any improvement in strength must be brought about primarily through the other factors. High-grade glue, insuring maximum tensile strength (fig. 1), should be chosen. In general, a thick consistency of glue solution gives better results than a thin one, so that the proportion of water in the mixture should be somewhat less than for side-grain gluing.

With even the most careful gluing of straight butt joints not more than about 25 per cent of the tensile strength of the wood parallel to the grain has been obtained in tests. It is evident, therefore, that in order to obtain a tensile strength of the various species that is greater than 25 per cent of the tensile strength of the wood, a scarf, serrated (fig. 9, H and I), or other form of joint must be used instead of plain end gluing. Where it is necessary to elongate members, such as longerons or beams, some such form of joint is recommended. The plain scarf (fig. 9, I) is perhaps the easiest to glue and involves fewer machining difficulties than the many angle forms (fig. 9, H).

DRYING AND CONDITIONING GLUED STOCK

The gluing operation adds moisture to the wood. Glue that has set in joints contains only a part of the water added at the time of mixing, the remainder being absorbed by the wood or removed by evaporation. The absorbed moisture must be allowed to dry out or to distribute itself through the wood in order to insure the full strength of the joint and to reduce the tendency of the glued member to warp.

Table 3 (p. 18) shows the percentages of moisture added to different constructions in gluing, calculated for a specified glue mixture and spread. No allowances have been made for surface evaporation, but the computed percentages are checked closely by actual determinations.

In propellers (fig. 9, F) and similar constructions, glued from thick laminations, the moisture from the glue need not be eliminated but may simply be allowed to distribute itself throughout the construction. Even complete equalization would require a very long time. For birch and white oak in laminations about three-fourths of an inch thick and under average room temperatures, a conditioning period of 7 to 10 days is sufficient. For quicker-drying woods, such as spruce, which permit a more rapid distribution, a 2-day period should suffice under most conditions. However, where constructions are glued from laminations one-fourth of an inch or less in thickness they will normally contain too much moisture and should be dried for one to three weeks or longer depending upon their thickness and width. A spruce bow end, for example (fig. 9, E), will usually dry sufficiently at room conditions during 7 to 10 days, but a thick laminated spar flange would require two or three times as long.

In plywood it is advisable to dry out by artificial methods a part, at least, of the moisture added in gluing, until the construction has reached the average service moisture content. Drying plywood to an excessively low moisture content materially increases warping, opening of joints, and other defects. It is therefore recommended that for the general requirements of aircraft, plywood be dried to an average moisture content of 10 to 12 per cent. This is somewhat lower than the average found in service (Table 2) but is higher than the moisture content in most fabricating shops in winter.

Tests have shown that it is possible to dry panels three-sixteenths of an inch or less in thickness very easily in 8 to 16 hours under relatively mild conditions. Satisfactory results may be obtained with a rather wide range of drying temperatures, such as 70° to 140° F., if proper relative humidities are used.

Table 9 shows several combinations of temperatures and relative humidities, which will produce a moisture content of 8 to 12 per cent in plywood panels within a reasonable drying period. If exposed for an indefinite period to the conditions outlined in Table 9, however, the plywood will come to a moisture content somewhat lower than those indicated. (Fig. 3.)

TABLE 9.—*Combinations of temperatures and relative humidities suitable for producing a moisture content of 8, 10, or 12 per cent in plywood panels*

Moisture content desired, per cent	Relative humidities for use with different temperatures						
	70° F.	80° F.	90° F.	100° F.	110° F.	120° F.	140° F.
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
8	30	31	32	33	35	37	41
10	43	44	45	46	48	50	53
12	55	56	57	58	59	61	65

RECOMMENDED PRACTICE FOR THE PRINCIPAL AIRCRAFT GLUING OPERATIONS

The following pages give a summary of information and specific recommendations on important details in the principal operations in the gluing of: (1) Propellers; (2) plywood; (3) laminated spars, spar flanges, bow ends, pontoon ribs, and reinforcing blocks; (4) scarf-type joints; (5) wing ribs; (6) box beams; and (7) general assembly.

Necessary prerequisites in all gluing operations are properly dried and machined stock, and equipment that spreads the glue and applies pressure uniformly over the joint. These requirements must be met or weak joints will result despite the most careful control of other conditions.

PROPELLERS

Propellers (pl. 3, B) are usually made in special propeller plants. Their gluing and shaping requires equipment not usually available in aircraft factories.

Most propellers are glued with animal glue. Casein glues are used only to a small extent, since their water resistance for this purpose is of little value. Birch, white oak, black walnut, and mahogany are the principal species of wood used.

A propeller-gluing operation requires several minutes for completion which, combined with the difficulty of gluing the species used, necessitates careful control of the gluing conditions. Since animal glue is largely used in propellers, most of the following details are applicable to animal glue:

GLUING ROOM

The gluing room should preferably be separated from the rest of the factory. A room temperature of 70° to 75° F. is recommended, but gluing may be successfully done at room temperatures of 85° to 90°. However, such high temperatures are uncomfortable for the workmen and are unnecessary.

GLUE

Glues conforming to the requirements given in United States Army and Navy Specifications Nos. 3–140 and 52G4C, respectively, are recommended.

GLUE-WATER PROPORTION

One part dry glue to 2¼ parts water (by weight) should be used for a glue that meets the minimum requirements of the foregoing specifications. (See preceding paragraph and p. 16.)

MOISTURE CONTENT OF WOOD

A moisture content of the wood at the time of gluing of approximately 8 per cent (p. 19) is recommended.

TEMPERATURE OF THE WOOD

Wood that is at approximately room temperature should be warmed at 85° to 90° F. for about one hour before applying the glue. Higher temperatures and shorter heating periods can also be used, but higher temperatures are more apt to lead to trouble.

GLUE SPREAD

One and one-fourth ounces of glue mixture should be spread uniformly per square foot of glue line. (If both sides of the joint are spread, 25 per cent more glue should be used.) A more uniform spread of glue is obtained by the use of mechanical spreaders than by hand spreading. The glue-coated wood should be laid together as soon as spread (closed assembly). (P. 24.)

ASSEMBLY TIME

A closed assembly time of 8 to 15 minutes or 10 to 18 minutes with wood warmed at 85° or 90° F., respectively, is recommended. Pressure should be applied not sooner than 15 or 18 minutes after the first lamination is coated with glue, but not later than 8 or 10 minutes after the last lamination is spread. (Table 5.)

PRESSURE

A pressure of 150 to 200 pounds per square inch of single-joint area should be applied for a minimum time of 5 hours. Pressure-distributing blocks, cut from trimmings from the laminations being glued, and cauls should be used to equalize the load over the joint areas. (Pp. 27 to 29.)

CONDITIONING

The glued blocks should be conditioned at room temperatures for at least two days before rough carving and five additional days before finish carving (p. 39).

PLYWOOD

Aircraft plywood is usually manufactured in plywood plants where large glue spreaders and power presses (pl. 13, A and B), not usually found in aircraft factories, are available.

Either blood-albumin or casein glues are successfully used in the manufacture of aircraft plywood. While a number of species of wood are permitted in aircraft-plywood specifications [21] the list of woods actually used in the past has consisted almost entirely of basswood, birch, mahogany, Sitka spruce, and yellow poplar.

Methods and practices that produce high-grade, water-resistant plywood have been developed (*3*, *20*). The hot-press method is used with blood-albumin glues and either the hot-press or the cold-press method with casein glues (p. 34). The following is a summary of recommended conditions for gluing aircraft plywood:

GLUING ROOM

Ordinary room temperatures and shop conditions are satisfactory.

GLUE

Highly water-resistant types of blood-albumin or casein glues (p. 2) are recommended.

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[21] The species permitted in plywood in the U. S. Army and Navy specifications are given in U. S. Army, Plywood, Aircraft, Specif. No. 82–6–A, 7 p., illus., 1928, and in U. S. Navy, Plywood (Aircraft Use), Dept. Specif. No. 39P13, 6 p., illus, 1929.

GLUE-WATER PROPORTION

A glue mixture of comparatively thick consistency (1 part by weight of dry glue to 1.8 to 2 parts of water) is recommended for most prepared casein glues. Spruce glues well with a somewhat thinner mixture than required for hardwoods (p. 35).

QUALITY OF VENEER

Smooth, tightly cut veneer that is free from bad cross grain and rot (p. 20) is recommended.

TEMPERATURE OF WOOD

Wood that is of ordinary room temperature is satisfactory.

GLUE SPREAD

One and one-fourth ounces of glue mixture per square foot of joint area should be applied evenly with machine spreaders, single spread (p. 23).

ASSEMBLY TIME

For blood-albumin glue an assembly time of 5 to 20 minutes (closed assembly) is recommended. For casein glue an assembly time of 3 to 15 minutes (closed assembly) is recommended. On spruce wood the assembly time may safely be extended to 18 or 20 minutes (p. 35).

PRESSURE

A pressure of 150 (for spruce and basswood) to 200 (for birch) pounds per square inch of panel area should be applied in the cold-press process for a minimum time of 5 hours. For the hot process, the pressing time depends upon thickness and number of panels pressed (p. 34).

DRYING

The glued panels should be dried to a moisture content of about 12 per cent (p. 39).

LAMINATED SPARS, SPAR FLANGES, BOW ENDS, PONTOON RIBS, AND REINFORCING BLOCKS

In laminating spars, spar flanges, bow ends, pontoon ribs, and reinforcing blocks several minutes may be required from the time the first glue is spread on the wood until pressure is applied. Furthermore, the large glue line areas of most of these members require large presses (pl. 12, A) or the use of many hand clamps (pl. 12, B) in order to obtain adequate pressure.

The gluing operations are somewhat simplified, however, in that spruce is the principal and often the only wood used, and the gluing is done with casein glues.

The following conditions are recommended for gluing Sitka spruce into laminated members:

GLUING ROOM

Ordinary room temperatures and shop conditions are satisfactory.

GLUE

Glue conforming to United States Army and Navy Specifications Nos. 98–14020–D and 52G8, respectively, is recommended.

GLUE-WATER PROPORTIONS

A glue mixture of medium consistency (by weight 1 part of dry glue to 2 parts of water) is recommended for most prepared glues (p. 15).

MOISTURE CONTENT OF WOOD

A moisture content of the wood at the time of gluing of 7 to 12 per cent, depending upon thickness of individual laminations and other factors (p. 17 and Table 3), is recommended.

TEMPERATURE OF WOOD

Wood that is at ordinary room temperature is satisfactory.

GLUE SPREAD

One and one-fourth ounces of glue mixture should be spread uniformly per square foot of joint area. (If both sides of joint are spread, 25 per cent more glue should be used.) Machine spreading is preferred. The glue-coated pieces should be laid together as soon as spread (p. 24).

ASSEMBLY TIME

Pressure should be applied within 20 minutes after glue is first spread on the wood. Where it is impractical to lay the pieces together as soon as coated with glue, the maximum assembly time should not exceed 8 minutes. (Table 5.)

PRESSURE

A pressure of 100 to 150 pounds per square inch of single joint area should be applied for a minimum time of 4 hours (pp. 30 to 32).

CONDITIONING

The glued members should be conditioned for at least two days at room temperature before machining. Where individual laminations are one-fourth of an inch or less in thickness the conditioning period should be one to three weeks, depending upon thickness and width of laminated member (p. 39).

In laminating hardwoods with casein glue, a glue mixture of thicker consistency (about 10 per cent less water than for spruce) should be used with an assembly time of 12 or 6 minutes for closed and open assemblies, respectively, and with a pressure of 150 to 200 pounds per square inch applied for at least 5 hours (p. 35).

SCARF-TYPE JOINTS

Scarf and finger, or serrate, joints (fig. 9, H and I) are frequently made in building long pieces, such as in laminations for beams and propellers. The gluing surfaces are partly end-grain wood.

The following procedure is recommended for gluing scarf and other end-grain surfaces in aircraft:

The end-grain surfaces should be sized with a glue mixture somewhat thinner than that used for regular gluing. A sizing mixture of 1 part glue to 3 parts water is recommended for animal and prepared casein glues that meet aircraft requirements. The sizing coat should be allowed to dry on the wood surfaces. The mixture for the final gluing should be thicker than for side-grain gluing—about 1 part by weight of glue to 1.8 and 2 parts water for casein and animal glues, respectively. Both surfaces of the joint should be coated with glue and approximately 200 pounds pressure per square inch applied. For animal glue care should be used that other conditions are maintained that will cause the glue to come to the proper consistency for pressing (p. 24).

With the above-recommended procedure, the slopes shown in Table 10 for plain scarf joints are considered necessary to produce joints as strong as the wood.

TABLE 10.—*Slopes of scarf joints recommended for several species of woods*

Species	Slope	Species	Slope
Red gum	1 in 8.	Red oak	1 in 15.
Yellow poplar	Do.	White oak	1 in 15.
Sitka spruce	1 in 10 (estimated).[1]	Black walnut	Do.
Honduran mahogany	1 in 10.	White ash	1 in 15 (estimated).[2]
Yellow birch	1 in 12		

[1] In tests, made on plain scarf wing-beam sections, it was found (8) that a slope of 1 in 10 was sufficient for Sitka spruce to develop practically 91 per cent of the full strength of the section in cross bending. The plain scarf was considered the best of 4 different kinds of scarfs tested, and it was concluded that tooth-planing did not increase the efficiency of the splice.

[2] There are no test data showing the maximum slope of scarf for white ash that will give the full strength of the wood. A comparison of white ash with other species tested as to strength and gluing properties ndicates that the slope should not be greater than 1 in 15.

In finger or serrate joints the same slopes may be used as in the plain scarf joint provided the parts of the joint fit accurately. The sharply angular forms of the finger or serrate joints, however, are more difficult to machine to obtain a perfect fit of the parts and are ordinarily more difficult to glue.

Glued scarf joints for aircraft have frequently been wrapped with tape or reinforced with rivets with the intent of increasing the factor of safety. The wrappings, however, are probably more harmful than beneficial. They are known to be relatively inefficient, and in all probability they reduce rather than increase the durability of the joint by favoring a high moisture content. On the other hand mechanical fasteners do not reduce the strength and durability of the glue and, if properly designed and applied, will preserve some strength in the joint in case the glue temporarily softens or permanently deteriorates in service.

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WING RIBS

Wing ribs are glued with casein glue. The principal species of wood used are Sitka spruce, mahogany, yellow poplar, and basswood. The gluing of the ribs involves the making of many joints of small size and is almost entirely a hand operation. The ribs are assembled in jigs or forms, the contact surfaces of the pieces are coated with glue, and brads are commonly inserted at the joints. This procedure is tedious, time consuming, and the gluing conditions are usually not the best (*22*).

In rib-gluing operations now commonly used, three conditions are apt to be unfavorable to the production of strong joints: (1) Irregular glue spreads; (2) too long an assembly time on some joints; and (3) inadequate pressure. The use of mechanical glue spreaders is recommended for obtaining more uniform glue spreads over the joints. Pressing the joints with clamps or other devices, either with or without the insertion of brads (pl. 14), is recommended for insuring more complete contact and stronger glue joints. Small rollers, revolving in a bath of glue, are sometimes used for spreading the glue on cap strips. (Fig. 19, A and B.) Similar equipment may be useful for coating stiffeners, diagonals, and other parts at the contact points. Pressure forms are also used successfully for gluing cap strips to the webs and gluing diagonals and stiffeners in place. These methods will doubtless increase as models and types of aircraft become more standardized and as the size of manufacturing operations increase. The use of such mechanical appliances for spreading and pressing tends to reduce the assembly time and will result in more economical production by gluing the ribs in multiples.

Most wood surfaces that are glued in rib construction are side grain, therefore the gluing conditions recommended for gluing Sitka spruce with casein glue into laminated construction (p. 43) are recommended for the gluing of wing ribs. However, in gluing the cap strips to the webs or ribs there may be involved the gluing of a certain amount of end-grain wood. The use of plywood in the web results in the end grains being exposed on approximately one-half the area of the edges. This condition necessitates bringing a larger area of the cap strip into contact with the plywood web, which can be done by setting the web into a groove in the cap strip (fig. 19, A), or by dividing the cap strip and gluing a piece to each side of the web (fig. 19, B). Because of the difficulty involved in bringing about perfect contact in the groove type of joint, the divided cap-strip type is easier to glue to obtain a perfect joint.

BOX BEAMS

The construction of box beams consists of gluing diagonals, or spacers, and reinforcing, or fitting blocks, between the flanges and of gluing plywood sheets to the sides. (Pls. 11 and 12, B and C.) Spruce is the prevailing wood for all parts, except the plywood, which commonly has either spruce or mahogany face plies.

Where reinforcing blocks, such as in Figure 19, C, *a*, and Plate 12, B, are glued into box beams at fitting points, the grain of the blocks is approximately parallel to the grain of the flanges or it may be at an angle of as much as 30°. Where the grain of the blocks is at an angle of as much as 30° or more the procedure recommended for gluing end-grain joints (p. 38) should be followed. Likewise, diaphragms used to stiffen a beam or hollow member, as shown in Figure 19, C, *b*, and E, *a*, and in Plate 11 involve the gluing of end-

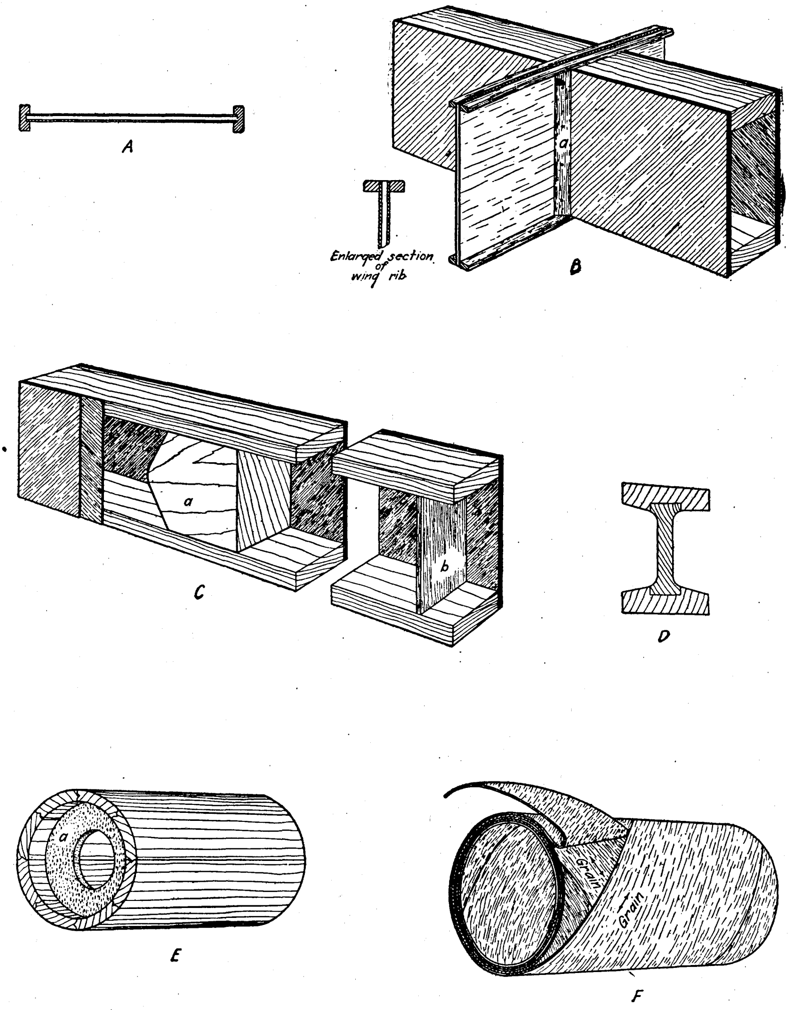


FIGURE 19.—Special joints made in aircraft: A, Section of wing ribs; B, wing rib-beam assembly; C, details of box-beam construction; D, cross section of laminated I beams; E, built-up laminated construction (airship); and F, wrapped veneer member

grain to side-grain wood wholly or in part, and the gluing directions for end-grain surfaces should be followed.

In gluing reinforcing blocks or spacers into box beams, clamps or other pressure devices are ordinarily used. (Pl. 12, B.) The clamps should be of such size and so spaced as to apply the proper amount of pressure per square inch of glue line area.

In gluing the plywood sides to the framework of box beams, both surfaces are side grain. (Fig. 19, B and C and pl. 12, C.) Nevertheless the joints are subjected to relatively severe internal stresses due to a difference in shrinkage with any moisture change of the cross-banded faces and the solid wood flanges. Allowable working stresses for such joints should be based on plywood rather than laminated wood values. Maximum strength of such joints is important, and the recommendations for gluing laminated members should be carefully followed (p. 43). In current practice pressure is often applied by the insertion of brads and in some instances by means of presses and clamps. Whether brads are used or not, it is desirable that pressure be applied in a press or by means of suitable hand clamps. Because of the size of the joint areas, however, it is recommended that jackscrews (fig. 13, F) or power presses be used, where practicable. If brads are used, the pressure may be applied either before or after their insertion. If applied afterwards the time elapsing between spreading the glue and pressing should not exceed 20 minutes. If pressed first, it is best to allow the glue to set for at least 5 or 6 hours before inserting the brads, but the joint need not be under pressure all that time. It is recommended that the pressure be applied for at least one-half hour.

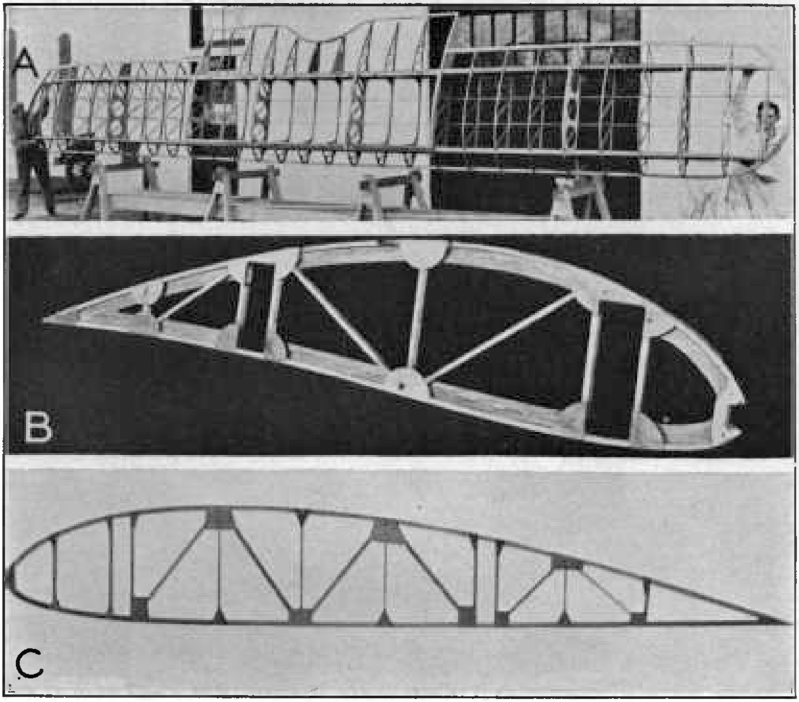
GENERAL ASSEMBLY

In wing assembly the ribs are fastened to the beams (pl. 15) and other parts and in some cases all or a part of the wing structure is covered with plywood. In most of the joints, side-grain faces are in contact, and recommendations for gluing laminated constructions should be followed (p. 43). The grain of adjacent pieces is frequently at right angles, however, and severe internal stresses occur on such joints with changes in moisture content of the wood, hence the necessity for careful gluing.

In gluing the cap strips of the ribs to the beams, precautions must be used to insure an adequate amount of glue uniformly applied to the joint area. Pressure should also be applied to these joints by means of clamps. This should be done even though brads or screws are used.

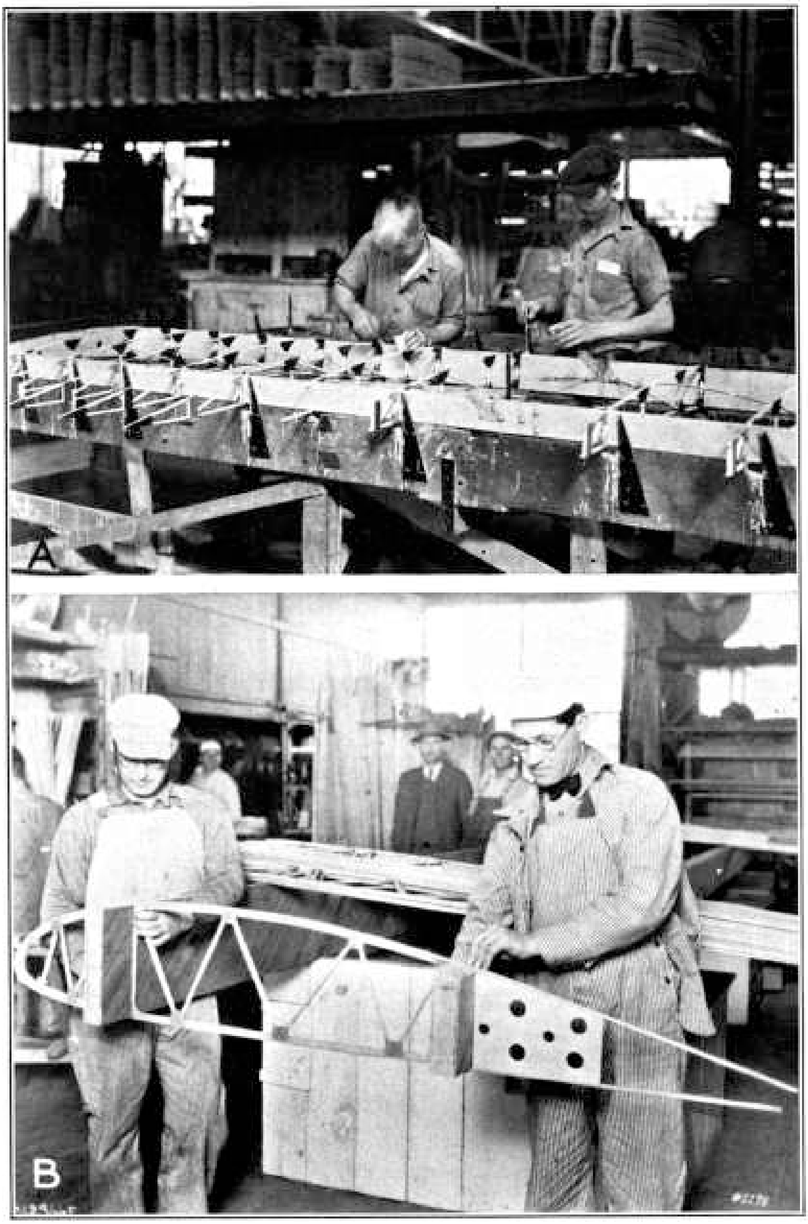
In the gluing of shear blocks to the beam and wing rib (shown in fig. 19, B, *a*), the grain of the blocks is across or diagonal to the face grain of both the rib and the beam, bringing into contact side-grain faces in a similar way as in plywood. The pieces are usually glued and nailed with brads, but the only pressure that is applied to the joints in gluing results from the insertion of the brads. This procedure is not likely to bring about complete contact with casein glue, owing to insufficient and nonuniform pressure, and the strength of the joints might therefore be expected to be erratic. A more reliable method is to apply pressure with small clamps and allow the glue to set. This may be done either immediately before or after the insertion of brads. Where regular clamping is not feasible a momentary application of the proper amount of pressure after inserting the brads will be better than no clamping at all.

Reinforcing blocks of hardwoods, such as ash, birch, maple, or oak, or of plywood are frequently glued to solid or laminated spruce



WINGS GLUED UNDER PRESSURE

A, All wood wing structure assembled without the customary brads. Pressure was applied with clamps or similar devices to all joints; B, wing rib glued in a jig under pressure. Pressure was applied to more than 50 joints and brads were used only to hold the pieces in place until pressed; C, the laminated cap strips of this wing rib were glued under pressure. The hundred odd joints between gussets and other parts of the rib were glued under pressure applied by inserting brads although such joints afford an opportunity for applying the pressure by power or clamp devices.



WING ASSEMBLY

A, Gluing the ribs to solid spruce spars of a biplane wing. Pressure is applied only by means of brads; B, starting to assemble a monoplane wing. Joints which hold the ribs and beams together are highly stressed and must be carefully glued.

beams at the fitting points. These joints should be glued under conditions recommended for gluing hardwoods with casein glue in laminated construction (p. 43), and pressure should be applied by means of clamps or presses.

In gluing plywood to the leading edge, to ailerons, or as a covering on wings or flying-boat hulls (pls. 2, A and 3, A) it is usually not practicable to apply pressure with present clamping devices.[22] Inasmuch as brads must be relied upon to apply pressure to the joints the glue should be of an easily flowing consistency and the assembly time should be as short as possible.

In Figure 19, D and E are shown two special types of shaped joints, involving the use of grooved construction to provide extra gluing area. For a general discussion of plane, tongue-and-groove, or other shaped joints, see page 20. When gluing refractory woods under conditions not favorable to the production of strong joints, the additional gluing surface provided by shaped joints may prove to be of some value, but with such woods as Sitka spruce and with good gluing conditions the additional gluing area is unnecessary, and the plain flat joints are as strong as the woods themselves.

PRINCIPLES OF CROSS-BANDED AND LAMINATED WOOD CONSTRUCTION

The making of satisfactory glued joints of any type depends not only on good gluing but also on proper design. The principles or rules that govern all glued-wood construction are based largely on the avoidance of internal stresses or the balancing of these stresses when necessarily present.

CROSS-BANDED CONSTRUCTION

Changes in the moisture content of wood induce or relieve internal stresses. In cross-banded constructions (fig. 9) these stresses are chiefly the result of the arrangement of the plies at different angles. Adjacent plies tend to shrink or swell across the grain under moisture changes; and since each ply, by reason of its small longitudinal shrinking or swelling, restrains the adjoining ply or plies, large internal stresses are set up in each layer. If the plywood is drying, all plies tend to shrink in the direction across the grain. Thus all plies are put in tension perpendicular to the grain and in compression parallel to the grain. There is, in fact, a shearing force at work on the glue joints. In plywood that is thus stressed from drying, moistening the plies tends first to relieve the stresses and, if continued far enough, to introduce the exactly opposite forces. Moistening and drying, therefore, alternate in their action, each at first correcting and finally reversing the effects of the other.

[22] A unique veneer gluing operation is employed in a Pacific coast aircraft factory in the construction of monoplanes. The fuselage, which is a monocoque type, is shaped and glued in a concrete form using compressed air to apply pressure. Single-ply veneer is first placed in the form, a coat of casein glue applied, and a second ply is then forced into position in the form by a bag of compressed air. The grains of the two plies are laid at right angles. This construction is reported to give great strength and positive alignment, with extremely light weight (*13*). A similar type of construction has been used in pontoons and flying-boat hulls; the veneer, which is glued with marine glue and fastened to the framework with brads or small nails, is applied as a covering.

BALANCED CONSTRUCTION

The stresses in cross-banded construction must be approximately balanced in the panel itself, or there will be a strong tendency toward distortion and warping. The necessary balance of forces is provided by using an odd number of plies and so arranging them that for any given ply there is a similar, opposite, and parallel ply equally distant from the core or central ply. As already explained, if two plies are glued together with the grain at a right angle, each ply tends to distort the other when any moisture change occurs, and cupping is the result. By using a third ply with the grain parallel to that of the other outside, or face ply, a balanced effect is produced. The corresponding plies should not only be parallel to each other and perpendicular to adjacent plies, but they should be of similar properties (*7*).

Obtaining symmetrically placed similar plies involves a consideration of: (1) Ply thickness, (2) kind of wood with particular reference to (*a*) shrinkage and (*b*) density, (3) moisture content of wood at time of gluing, and (4) angle or relative direction of grain of plies.

It is possible to get a balanced construction without having a strictly parallel-and-perpendicular arrangement of plies. The wing-beam section shown in Figure 19, C, illustrates a variation from the 90° arrangement of plies in which an approximate balance of internal stresses is still maintained in the member as a whole. The plies should be symmetrically arranged about the core and for each pair of opposite plies at any angle other than 0° or 90° with the core there must be a corresponding pair of plies with the grain at a right angle to that of the first pair. This principle applies only to five or a larger odd number of plies. In some aircraft parts, however, freedom from warping tendencies is of less importance than other mechanical characteristics, and more or less complete departures from the principle of balanced construction become necessary.

The amount of internal stress on the glue joints of cross-banded construction is determined chiefly by the thickness of the plies and the density and shrinkage of the woods involved. Thick layers and woods of high density and high shrinkage properties develop the largest stresses. Table 11 contains shrinkage and density values for a number of woods which are now glued for aircraft together with several woods whose properties or abundance indicate that they may eventually be used. In plywood the face plies, being restrained on only one side, exert a relatively large stress on the outer glue joints. For this reason face plies should, in general, be thinner than the interior plies. One-eighth inch is about the maximum thickness of face plies that can be held securely in place under severe moisture changes, and where considerable strength of joint is required thinner plies must be used.

TABLE 11.—*Shrinkage and density of woods glued for aircraft* [1]

Species	Shrinkage [2] Tangential	Shrinkage [2] Radial	Density [3]	Species	Shrinkage [2] Tangential	Shrinkage [2] Radial	Density [3]
	Per cent	*Per cent*			*Per cent*	*Per cent*	
Mahogany (Swietenia species)	4.7	3.4	0.46	Red oak	8.2	4.0	0.63
Northern white pine	6.0	2.3	.39	White ash (second growth)	8.7	5.3	.64
Western yellow pine	6.3	3.9	.41	Yellow birch	9.2	7.2	.63
Yellow poplar	7.1	4.0	.41	White oak	9.0	5.3	.69
Black cherry	7.1	3.7	.51	Cottonwood, eastern	9.2	3.9	.43
Black walnut	7.1	5.2	.57	Sugar maple	9.5	4.9	.62
Sitka spruce	7.5	4.3	.38	Basswood	9.3	6.6	.38
Tupelo gum	7.6	4.2	.52	American elm	9.5	4.2	.51
Sycamore	7.6	5.1	.50	Red gum	9.9	5.2	.49
Douglas fir (west coast)	7.8	5.0	.51	Beech	10.6	4.8	.63
Red maple	8.2	4.0	.54				

[1] Data from U. S. Dept. Agr. Tech. Bul. 158 except for mahogany (*18*).
[2] Shrinkage from green to oven-dry conditions expressed in percentage of dimensions when green. Longitudinal shrinkage of normal wood ranges from 0.1 to 0.3 per cent.
[3] Density expressed as specific gravity based on oven-dry weight and air-dry volume. They are the specific gravities used in plotting Figure 18 and are on a different basis from that used in certain tables of strength values of various woods for use in airplane design (*26, 27*).

In certain types of cross-banded construction the magnitude of the external stresses is of considerable importance. If, for example, the shear block in Figure 19 B, *a*, were glued to a solid wing beam, the glue would be subjected to very large shearing stresses during moisture changes, and failure might occur from this cause alone. The use of a plywood web on the beam greatly reduces the stresses on the joint because the shrinkage of the plywood and that of the block endwise are not greatly different.

LAMINATED-WOOD CONSTRUCTION

Propellers are an important example of laminated construction in airplane work. In laminated construction (fig. 9, E, F, G) the grain of plies is approximately parallel, and the shrinkage of all plies combined is similar to that of solid wood.

However, no two pieces of wood are exactly alike in properties. When glued together, even with the grain parallel, laminations with different shrinkage properties develop stresses at the glued joints, which weaken the member and cause it to change shape. In most laminated construction, and especially in propellers, it is of the highest importance that such stresses be avoided.

The construction of laminated-wood products free from internal stresses involves the principle of combining pieces of similar properties, which, in turn, necessitates a consideration of (1) the kind of wood, (2) the plane of cutting and direction of grain of pieces, and (3) the moisture content of plies.

Pieces of wood of the same species are more apt to be alike than pieces of different species. Variations in wood affecting its use in laminated construction are mainly shrinkage (Table 11) and rate of change in moisture content. A joint made of woods that have about the same rate of moisture change will be freer from stresses than one which includes both quick and slow changing woods. Contrary to the effect noted in cross-banded construction, differences in density of adjacent laminations, when not accompanied by differences in shrinkage properties, do not induce serious internal stresses.

Combining high and low density laminations of the same species, provided they are otherwise alike, into the same laminated construction does not appear to cause internal stresses of large magnitude. Laminated specimens under test have shown little weakening or tendency to warp from this cause (*14*).

There is a difference in shrinkage between quartered and flat-sawn material of the same species. Although this difference is greater in some woods than in others, an average of 150 species of wood shows a tangential shrinkage of about 8 per cent and a radial shrinkage of about 4½ per cent between the oven-dry and saturated conditions (*16*). Combining quartered and flat-sawn material is a disturbing factor in certain classes of laminated construction, such as propellers, but may be relatively unimportant in others.

The direction of the grain of adjacent laminations affects the strength and shape of glued members. Cross grain in a lamination results in a certain amount of longitudinal shrinkage of that particular lamination, whereas the longitudinal shrinkage of straight-grained material is very small or negligible. Consequently a construction made of cross-grained and straight-grained laminations is very likely to warp.

Stresses in laminated members resulting from differences of moisture content in the laminations have been found to disappear gradually and without danger of later recurrence if the glued block is kept for a long time in the same atmospheric condition, because the member checks or changes shape more or less to relieve the stressed condition of the fibers. If, however, the original stresses are the result of combining quartered and flat-sawn material they may die out during a long conditioning, but as soon as the atmospheric conditions change the stresses will be set up anew.

In general, then, it should be apparent that for laminated-wood articles in which high strength and accurate shape are required all plain-sawed or all quarter-sawed material of the same wood or similar woods should be used, and all pieces should be at a uniform moisture content when glued. For the manufacture of articles where slight changes in form are of no consequence, these precautions are of the United States:

GLUE FORMULAS FOR USE IN AIRCRAFT

The following water-resistant glue formulas, with directions for mixing, were developed at the Forest Products Laboratory by the laboratory personnel and are available for the free use of the people of the United States.

CASEIN GLUE FORMULA NO. 11 [23]

Ingredients	Parts by weight
Casein	100
Water	220–230
Hydrated lime	20– 30
Water	100
Silicate of soda (water glass)	70
Copper chloride	2– 3
Water	30– 50

[23] This formula, developed at the Forest Products Laboratory, is covered by U. S. Patent No. 1,456,842, which is available for the free use of the people of the United States. BUTTERMAN, S., and COOPERRIDER, C. K. PROCESS OF MANUFACTURING WATERPROOF ADHESIVES. (U. S. Patent No. 1,456,842.) U. S. Patent Office, Off. Gaz. 310: 1129. 1923.

The 220 to 230 parts of water added to the casein is approximately the right amount to use with Argentine (naturally soured) casein; but if a different casein is used, the water requirement will lie somewhere between 150 and 250 parts by weight.

The formula presupposes that a high-calcium lime will be used. A lime of lower grade may be used, but a proportionately larger amount of it will have to be added unless one is willing to sacrifice the water resistance of the glue. It is suggested that the user try 25 parts of lime to begin with. If this does not give good results, the amount can be varied within the limits specified.

The density of the silicate of soda used should be about 40° Baumé with a silica-soda ratio of from 1 to 3.25. Copper sulphate can be substituted for copper chloride.

The casein and water are placed in the bowl of the mixing machine, and the paddle is made to rotate, stirring the mixture until all the water has been absorbed and all the casein moistened. By allowing the casein to soak beforehand for a while it is more readily dissolved in the mixing process. In a separate container the hydrated lime is mixed with water. This mixture is stirred vigorously at first, but just before it is added to the casein it should be stirred with a gentle rotary motion, just enough to keep the finest particles of lime in suspension. Pour this milk of lime quickly into the casein.

When casein and lime are first combined they form large lumps, which are balls of casein coated with the partly dissolved casein. These balls break up readily under the action of the mixer, becoming smaller and smaller and finally disappearing. The solution, in the meantime, is becoming thin and fluid. Within the first minute after adding the lime it is well to stop the paddle and scrape the sides and bottom of the can, and then stir again. If a deposit of casein remains unacted on, it may cause more lumps later.

When about two minutes have elapsed since the lime and casein were first put together, it will be noticed that the glue has begun to thicken a little. The sodium silicate must be added now, or else the glue will become too thick. Disregarding lumps in the casein, if they are but few, pour in the sodium silicate. The glue will become even thicker momentarily, but it will soon change to a thin, smooth, and fluid consistency.

The stirring should continue until the glue is free from all lumps. This should not take more than 15 or 20 minutes, counting from the time the lime was added. If the glue is now a little too thick, a small amount of water may be added. If the glue is too thin, however, it will be necessary to discard the entire batch and start over again, using a smaller proportion of water.

The copper salt may be added at different times during the mixing process with apparently the same final results. If added as a powder or a solution to the casein before soaking, it is likely to have a corrosive action on the metal container, and for this reason it is advisable to add it later during the mixing process. If added at first, however, it should be thoroughly mixed with the casein before the addition of the lime. It may be placed in solution and conveniently stirred into the moistened casein immediately before adding the lime or after all the other ingredients have been combined and the mixture rendered smooth and uniform in consistency. When added at the end of the mixing period, it should be poured into the glue in a thin stream and the mixture stirred vigorously. Stirring should be continued until any lumps that may have formed at first by coagulation, when glue and copper solution mix, are broken up and a smooth, violet-colored glue is obtained.

Glue prepared by formula No. 11 has proved to be exceptionally strong and durable in aircraft construction, even under wet or damp conditions.

CASEIN GLUE FORMULA NO. 4B [24]

Formula No. 11, as above specified but without the copper-chloride solution, represents an earlier stage of development, known as formula 4B. The mixing is the same as for formula No. 11, except for the omission of the copper-chloride solution. The glue has a medium consistency, excellent working properties, and a good working life. It falls somewhat short of formula No. 11 in water-resisting properties, however.

BLOOD-ALBUMIN GLUE—HOT-PRESS FORMULA [25]

Ingredients	Parts by weight
Blood albumin (90 per cent solubility)	100
Water	170
Ammonium hydroxide (specific gravity 0.90)	4
Hydrated lime	3
Water	10

Cold water should be poured over the blood albumin and the mixture allowed to stand for an hour or two without stirring. The soaked blood albumin can then be put into solution with a small amount of stirring. After the blood albumin is in solution the ammonia is added while the mixture is being stirred slowly. Slow stirring is necessary to prevent foamy glue. The lime is then combined with the smaller amount of water to form milk of lime. The milk of lime is added and agitation should be continued for a few minutes. Care should be exercised in the use of the lime, inasmuch as a small excess will cause the mixture to thicken and become a jellylike mass. The glue should be of medium consistency when mixed and should remain suitable for use for several hours. The exact proportions of blood albumin and water may be varied as required to produce a glue of greater or less consistency or to suit a blood albumin of different solubility from that specified.

PARAFORMALDEHYDE-BLOOD-ALBUMIN GLUE FORMULA [26]

Ingredients	Parts by weight
Blood albumin (90 per cent solubility)	100
Water	140–200
Ammonium hydroxide (specific gravity 0.90)	5½
Paraformaldehyde	15

[24] This formula, developed at the Forest Products Laboratory, is covered by U. S. Patent No. 1291396, which is available for the free use of the people of the United States. BUTTERMAN, S. PROCESS OF MANUFACTURING WATERPROOF ADHESIVES. (U. S. Patent No. 1291396.) U. S. Patent Office, Off. Gaz. 258: 354. 1919.

[25] This formula, developed at the Forest Products Laboratory, is covered by U. S. Patent No. 1329599, which is available for the free use of the people of the United States. HENNING, S. B. GLUE AND MANUFACTURING SAME. (U. S. Patent No. 1329599.) U. S. Patent Office, Off. Gaz. 271: 48. 1920.

[26] This formula, developed at the Forest Products Laboratory, is covered by U. S. Patent No. 1459541, which is available for the free use of the people of the United States. LINDAUER, A. C. BLOOD-ALBUMIN GLUE. (U. S. Patent No. 1459541.) U. S. Patent Office, Off. Gaz. 311: 669. 1923.

The blood albumin is covered with the water and the mixture is allowed to stand for an hour or two, them stirred slowly. The ammonium hydroxide is next added with more stirring. Then the paraformaldehyde is sifted in, and the mixture is stirred constantly at a fairly high speed. Paraformaldehyde should not be poured in so rapidly as to form lumps nor so slowly that the mixture will thicken and coagulate before the required amount has been added.

The mixture thickens considerably and usually reaches a consistency where stirring is difficult or impossible. However, the thickened mass will become fluid again in a short time at ordinary temperatures and will return to a good working consistency in about an hour. It will remain in this condition for 6 or 8 hours, but when the liquid finally sets and dries, as in a glue joint, it forms a hard and insoluble film.

This glue may be used in either hot or cold presses. When cold pressed, however, it has only moderate strength, and for that reason is not to be depended upon in aircraft construction where maximum strength is required. If hot pressed, it is high in strength and very water resistant.

WATER-RESISTANT ANIMAL GLUE FORMULA [27]

Ingredients	Parts by weight
Animal glue	100
Water	225
Oxalic acid	5.5
Paraformaldehyde	10

The glue is soaked in the water until the granules or flakes have been softened. It is then melted at about 140° F. after which the temperature is allowed to fall to between 105° and 115°. The oxalic acid, in small crystals, and the paraformaldehyde, ground to a fine white powder, are then mixed together and added to the glue. The mixture is stirred until all of the oxalic acid has gone into solution, after which it is ready for use. The paraformaldehyde does not readily dissolve in the glue, and much of it remains as a finely divided solid during the working life of the glue mixture. A certain amount of agitation is, therefore, necessary to keep it evenly distributed throughout the mixture. The paraformaldehyde should be fine enough to pass through a 50-mesh sieve.

The paraformaldehyde for use in this formula should be of the slow-reacting type. A fast-reacting paraformaldehyde appreciably shortens the working life of the glue mixture.

If kept at a temperature not exceeding 115° F., the glue will remain in a fluid condition for 8 to 10 hours from the time of incorporating the paraformaldehyde and oxalic acid, after which it will set to a tough, firm jelly which can not be melted again. It is important to avoid heating the glue mixture much above 115° if a long working life is required. Organic decomposition of the glue will not seriously affect the quality of the glue at this temperature, since the chemicals used in its preparation act as preservatives.

[27] This formula, developed at the Forest Products Laboratory, is covered by U. S. Patent No. 1712077, which is available for the free use of the people of the United States. HRUBESKY, C. E., and BROWNE, F. L. WATER-RESISTANT ANIMAL GLUE. (U. S. Patent No. 1712077.) U. S. Patent Office, Off. Gaz. 382:201. 1929.

Both oxalic acid and paraformaldehyde are poisonous materials and should therefore be handled with care.

This glue combines the desirable characteristics of an animal glue with a relatively high-water resistance. However, the water resistance varies directly with the temperature of the water to which the glued article is subjected. At room temperatures the glue is highly water resistant, but at 140° F. it is very low in water resistance. The joints should be conditioned for about two weeks at room temperature to allow the glue to reach its maximum water resistance.

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